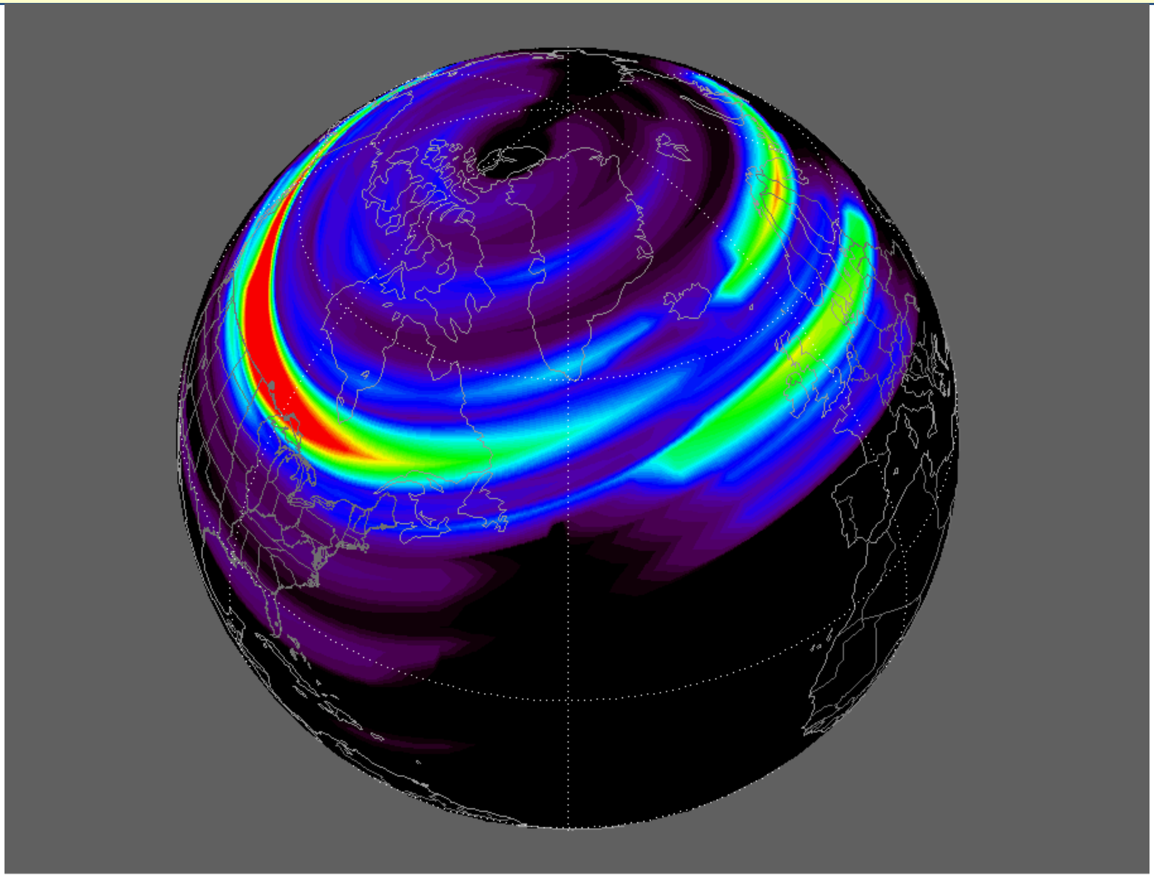
Electric Power Grids & Severe Space Weather:
Preparing US Power Grids and Understanding the Societal and Economic Impacts



Storm Analysis Consultants

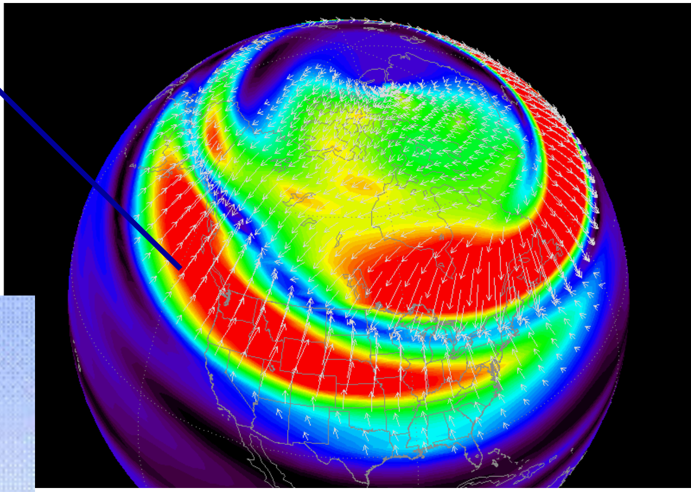
John G. Kappenman

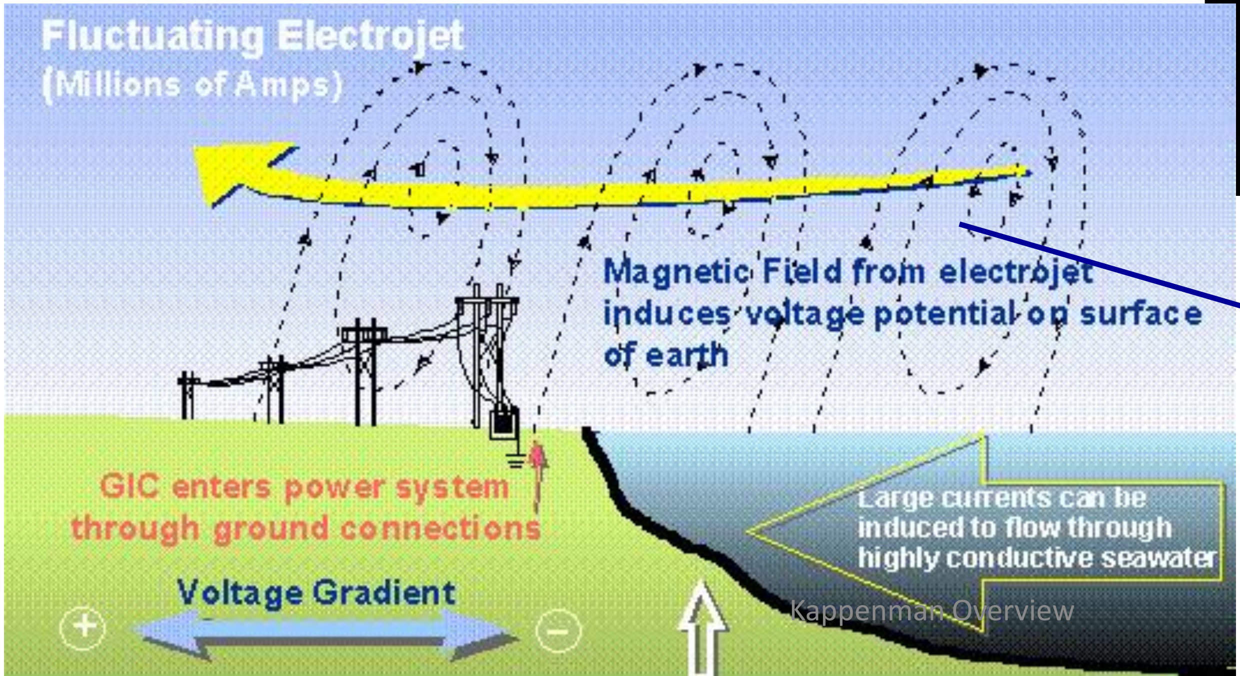
jkappenma@aol.com
218-727-2666

A Review of Power Grid Vulnerability to Solar Activity & Geomagnetic Storms

A rapidly changing geomagnetic field over large regions will induce Geomagnetically-Induced Currents (i.e. GIC a quasi-DC current) to flow in the continental interconnected Electric Power Grids

Geomagnetic Storms have Continent-Wide & Planetary Footprints





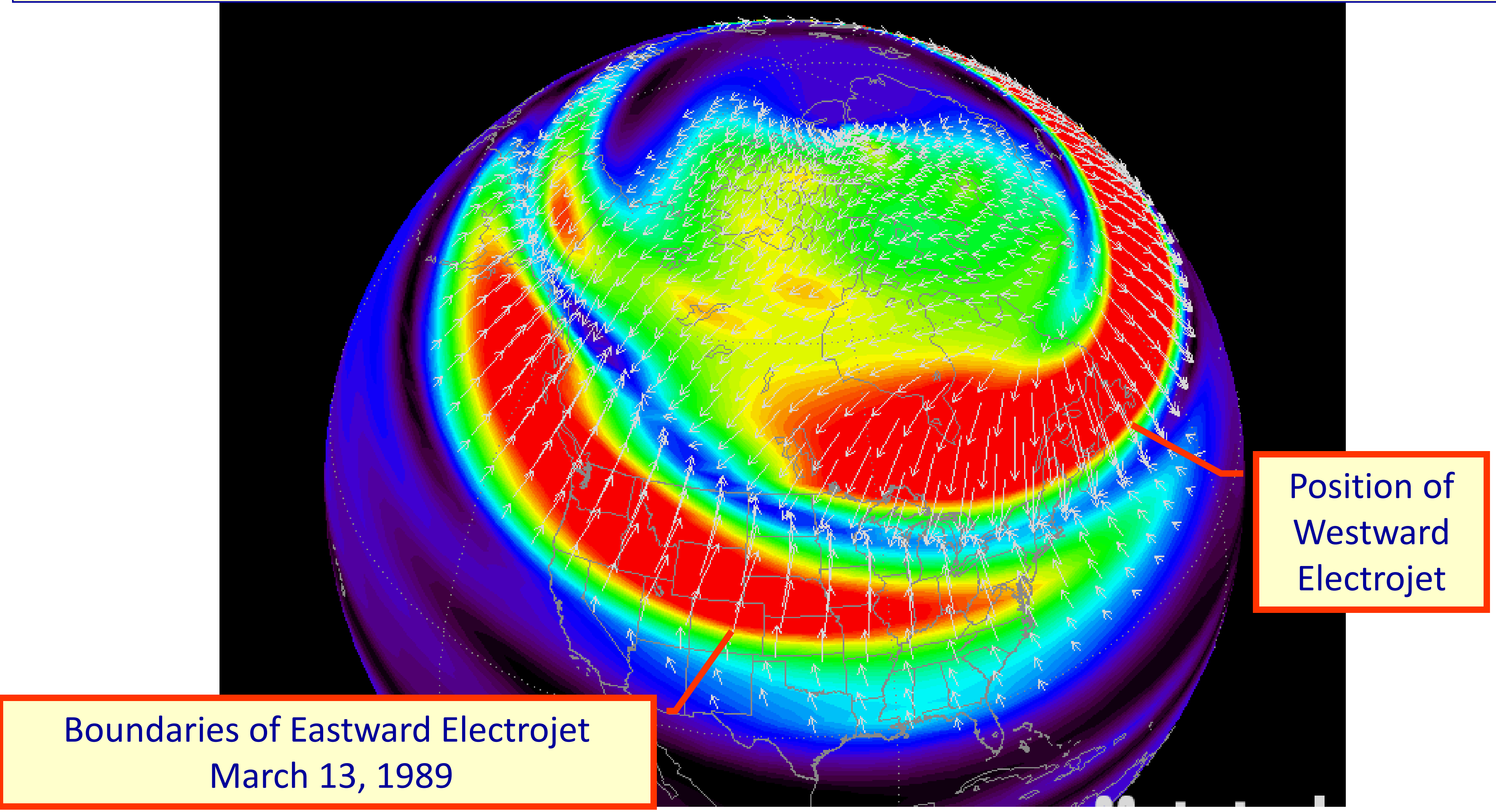
Storm causes Geomagnetic Field Disturbances from Electrojet Current that couple to Power Systems

Great Geomagnetic Storms & EMP

US Electric Grid Vulnerability -Trends and Preparedness

- **Threat**
  - **New Awareness that Geomagnetic Storm Severity is 4 to 10 Times larger than previously understood – Past Metrics did not measure risks correctly for power industry**
- **Vulnerability**
  - **Power Grid infrastructures have experienced a "Design Creep" over past few decades that have unknowingly escalated vulnerability to these threats** – No Design Code Yet Exists
- **Consequences**
  - **Power Supply is an essential scaffolding of modern society (40% of US Energy Supply)**
  - **All other Critical infrastructures will also collapse with long-term loss of Electricity – Society "Interdependency Creep"**
- **Risk** – Events have catastrophic potential, Immediate serious impacts to Society, Millions of Lives At-Risk and impact to future generations of society

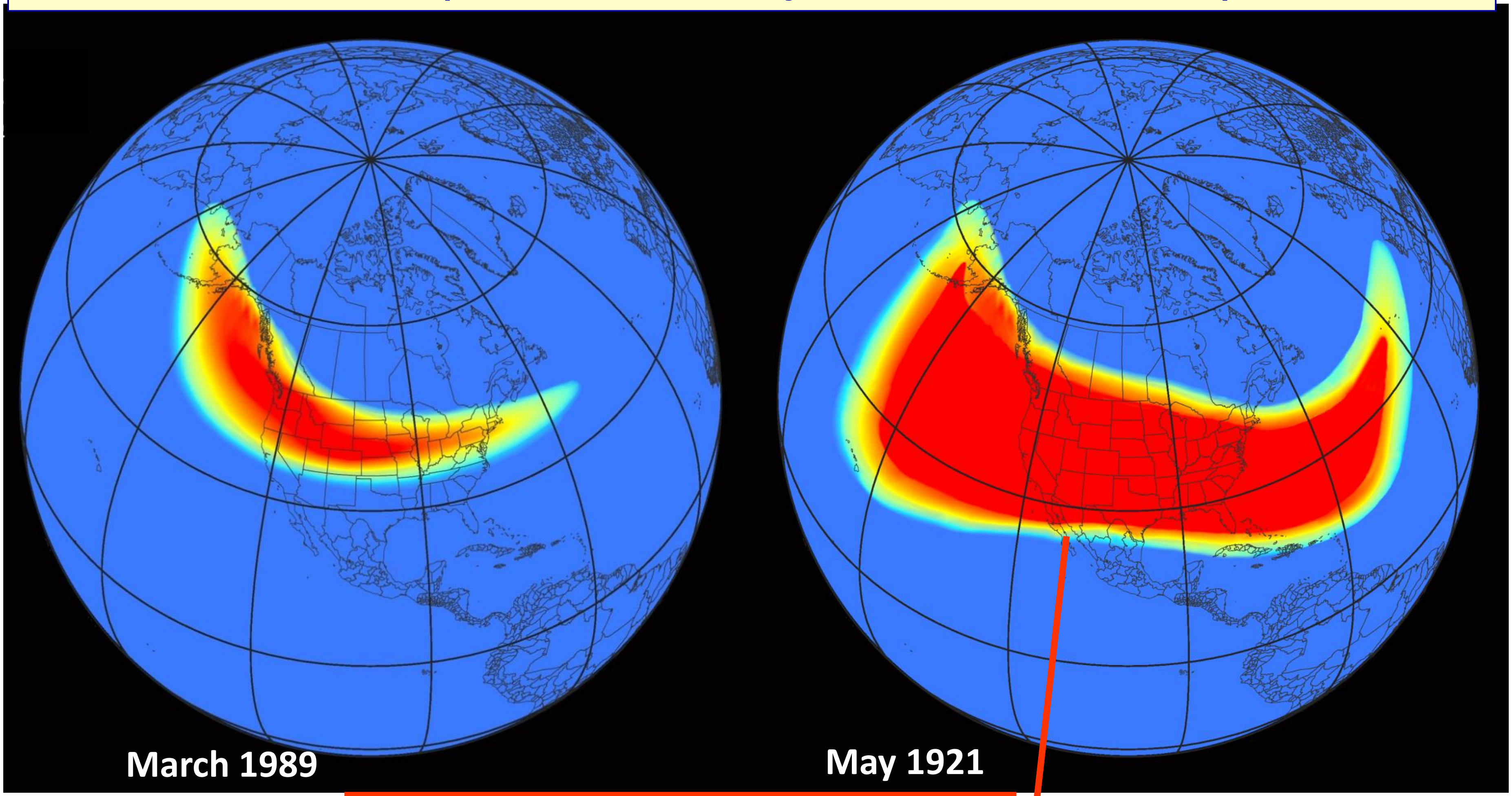
Storm Environments & Great Geomagnetic Storms
March 1989 Superstorm & May 1921 Storm Comparisons



Focus has largely been on Electrojet Intensifications, Other Processes are also Important At High, Low and Mid Latitude Locations around the World

Great Geomagnetic Storms

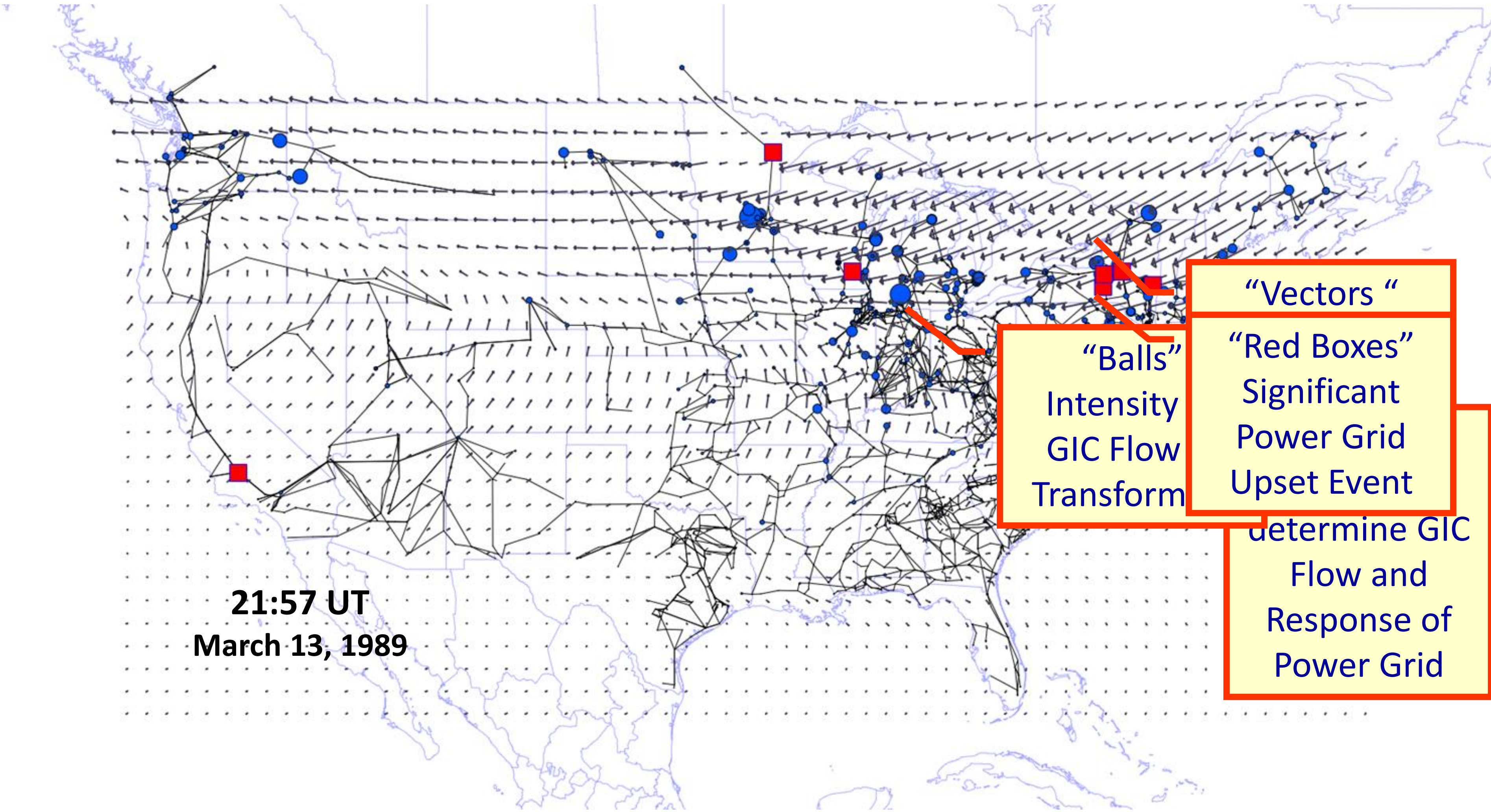
March 1989 Superstorm & May 1921 Storm Comparisons



May 1921 Storm and 1859 Storm were not only more Intense but had larger Geographic Laydown

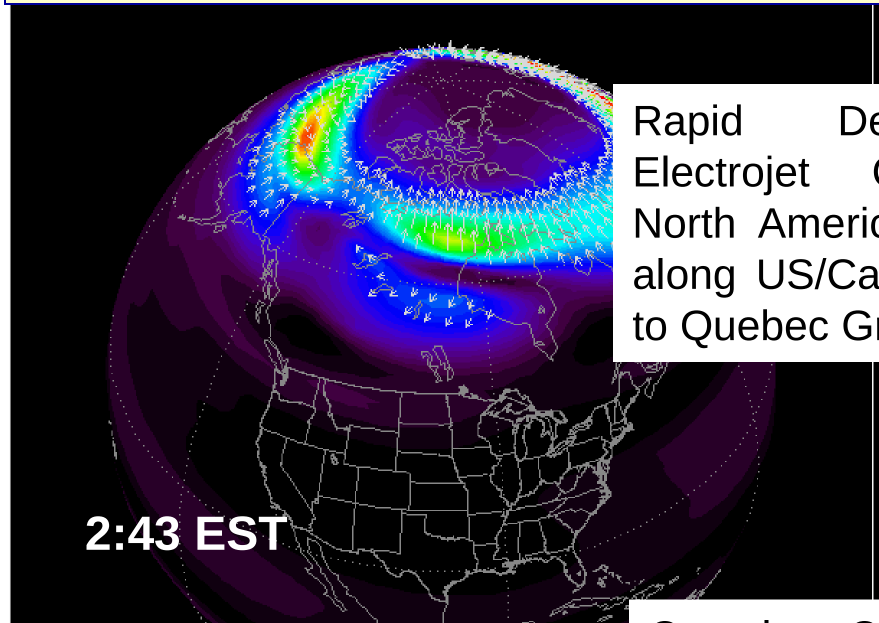
Geo-Electric Field & Power Grids

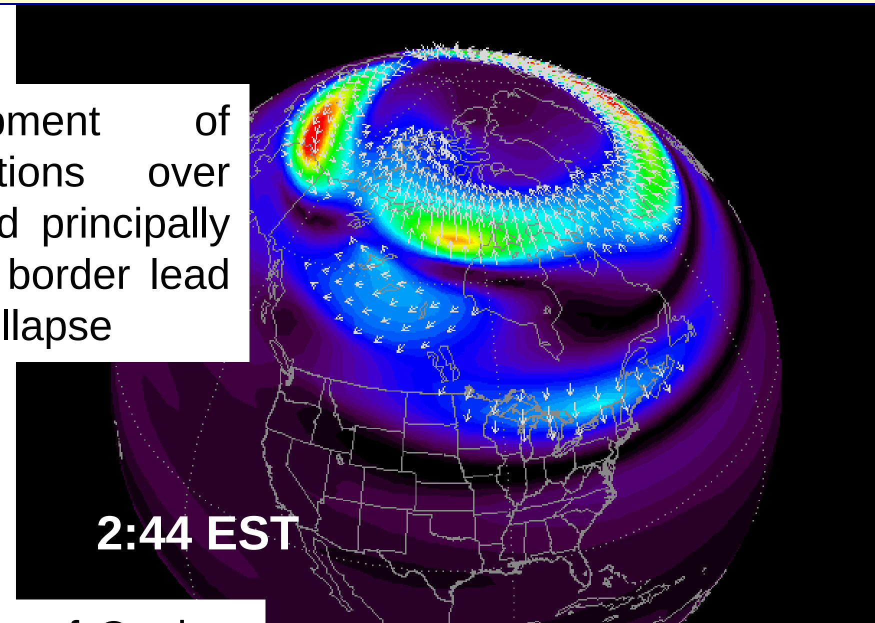
Intensity of Field, Modeling of GIC Flows



Storm Analysis Consultants

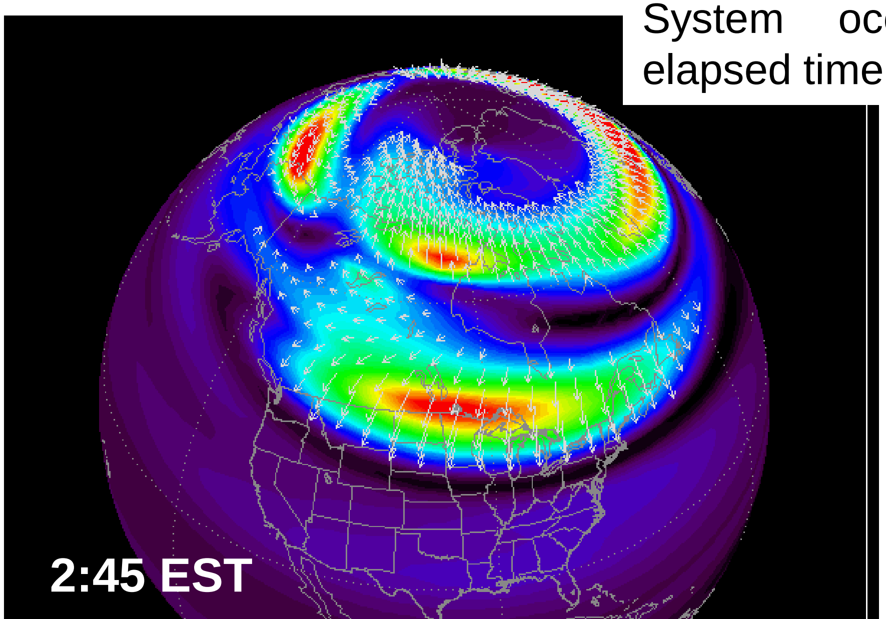
March 13, 1989 – 4 Minutes of a Geomagnetic Storm

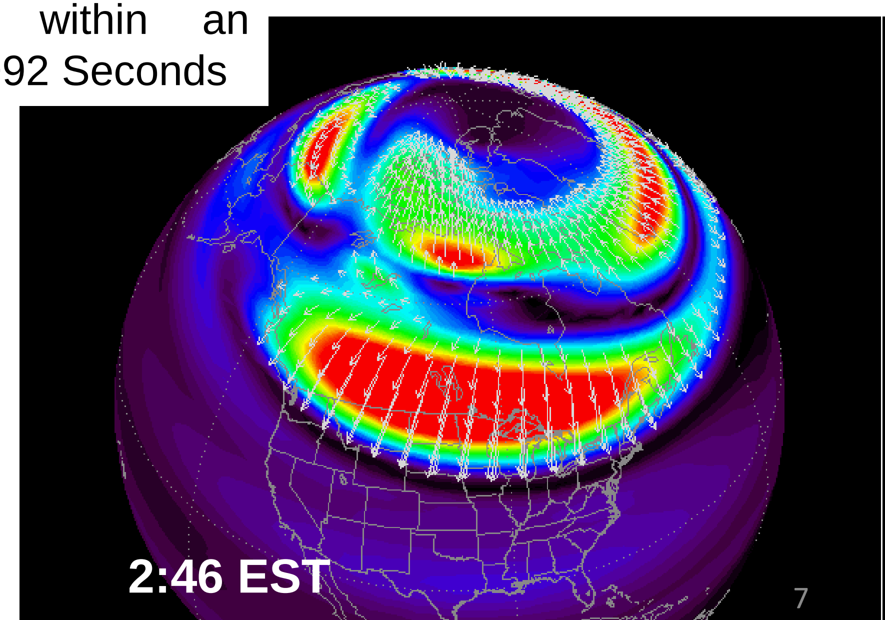




Rapid Development of Electrojet Conditions over North America and principally along US/Canada border lead to Quebec Grid Collapse

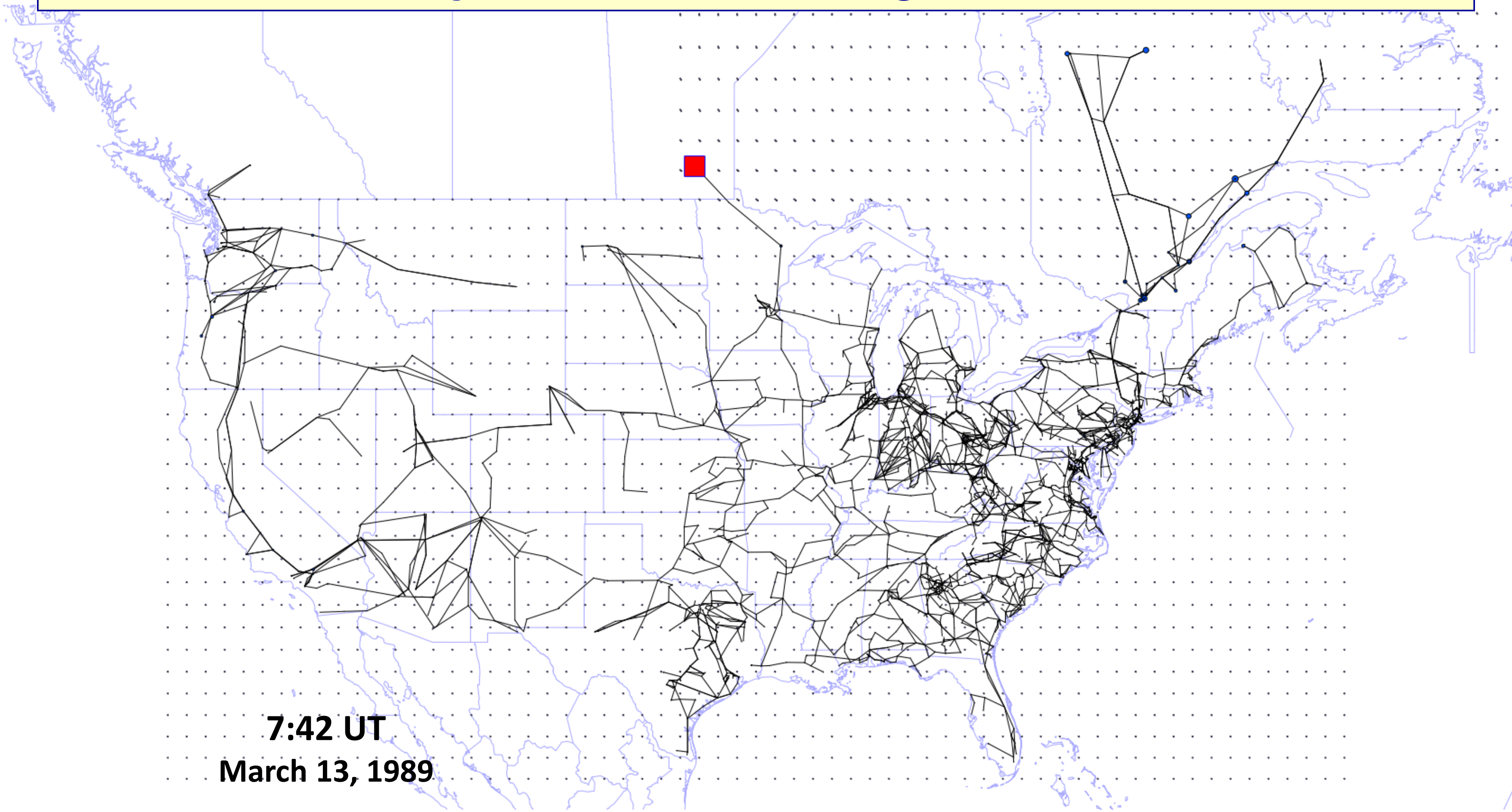
Complete Collapse of Quebec System occurs within an elapsed time of ~92 Seconds





Geo-Electric Field & Power Grids

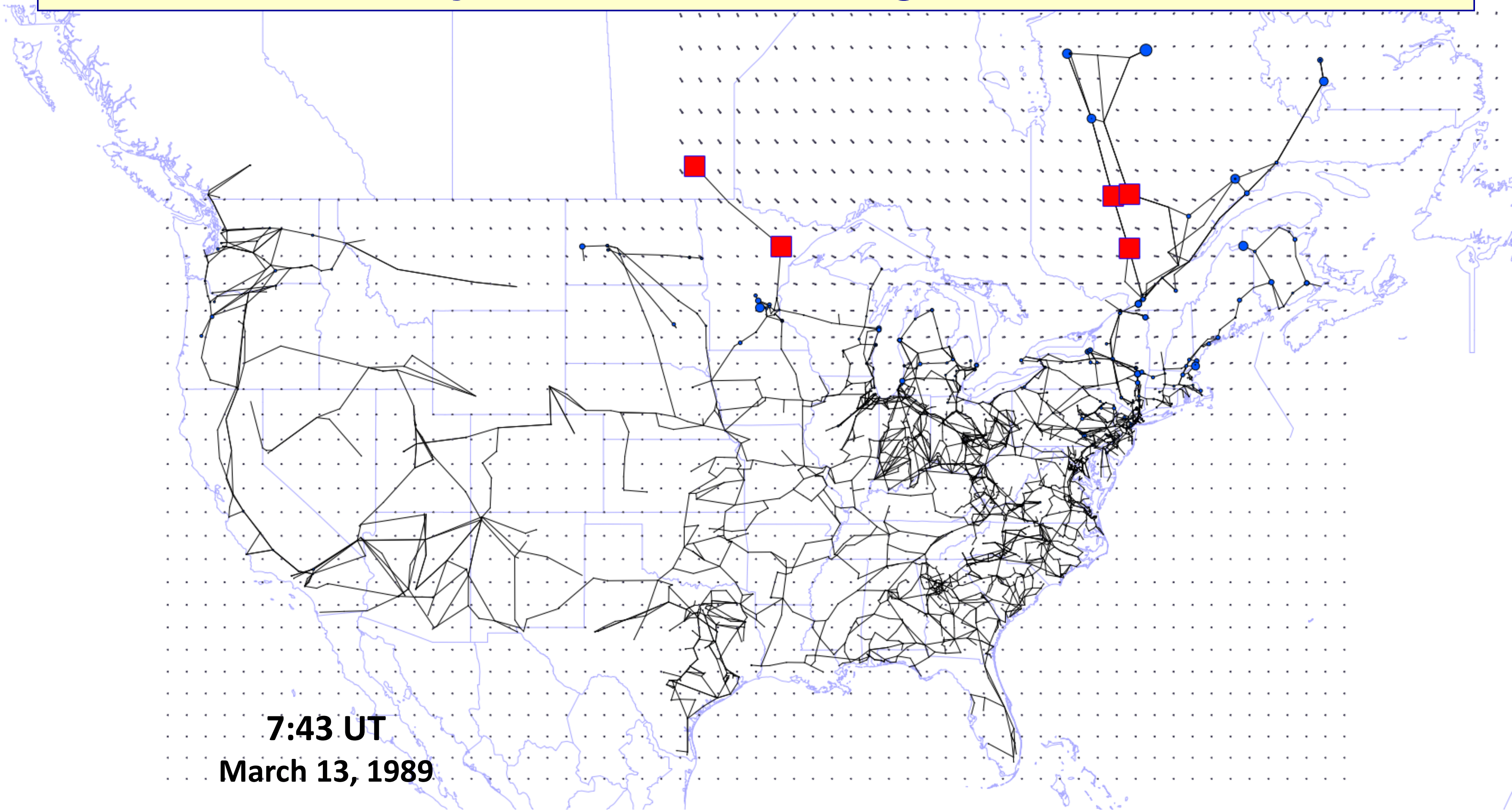
Intensity of Field, Modeling of GIC Flows



Early Substorm which caused Quebec Power Grid Collapse

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows

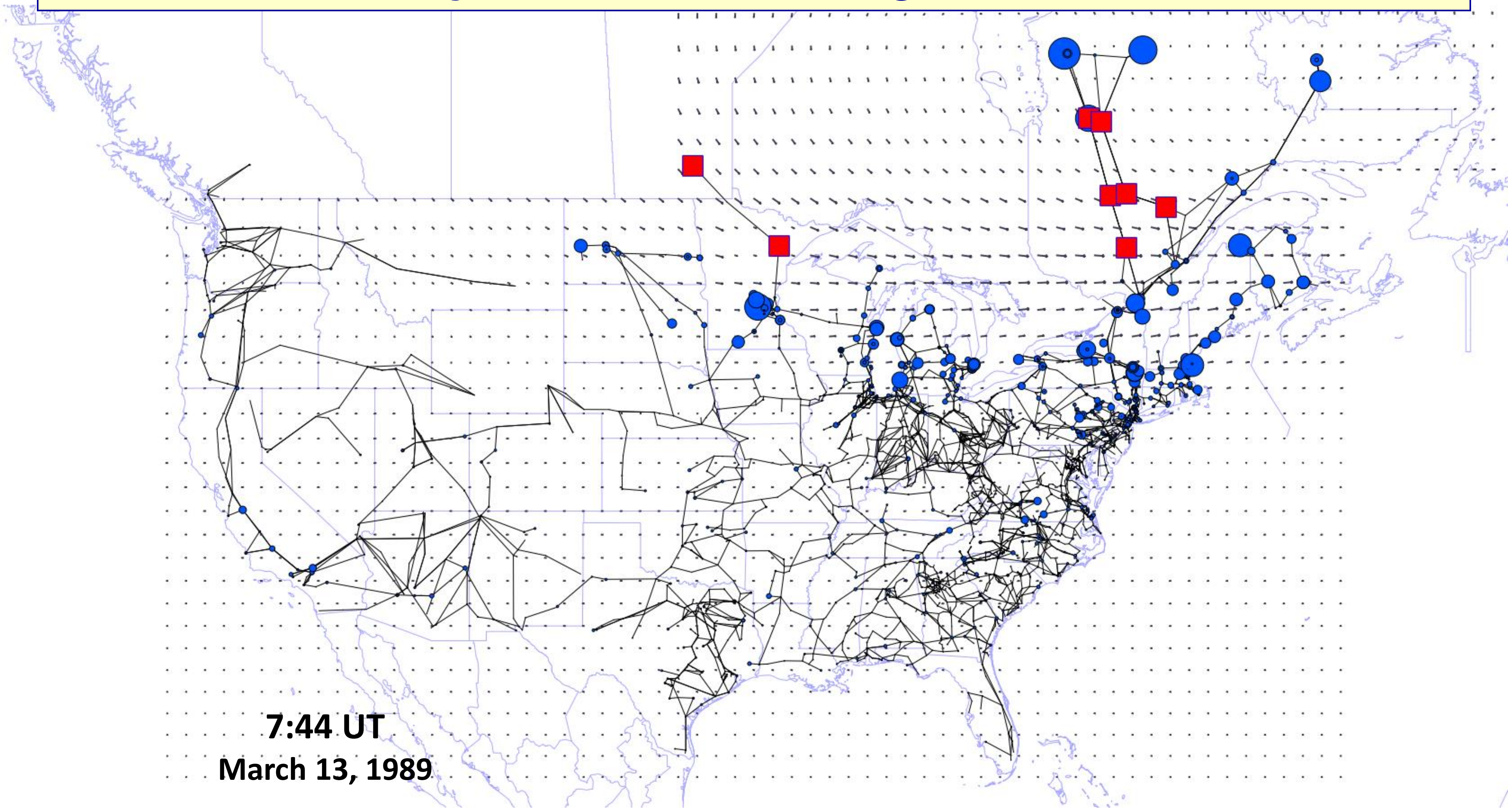


Early Substorm which caused Quebec Power Grid Collapse

Storm Analysis Consultants

Geo-Electric Field & Power Grids

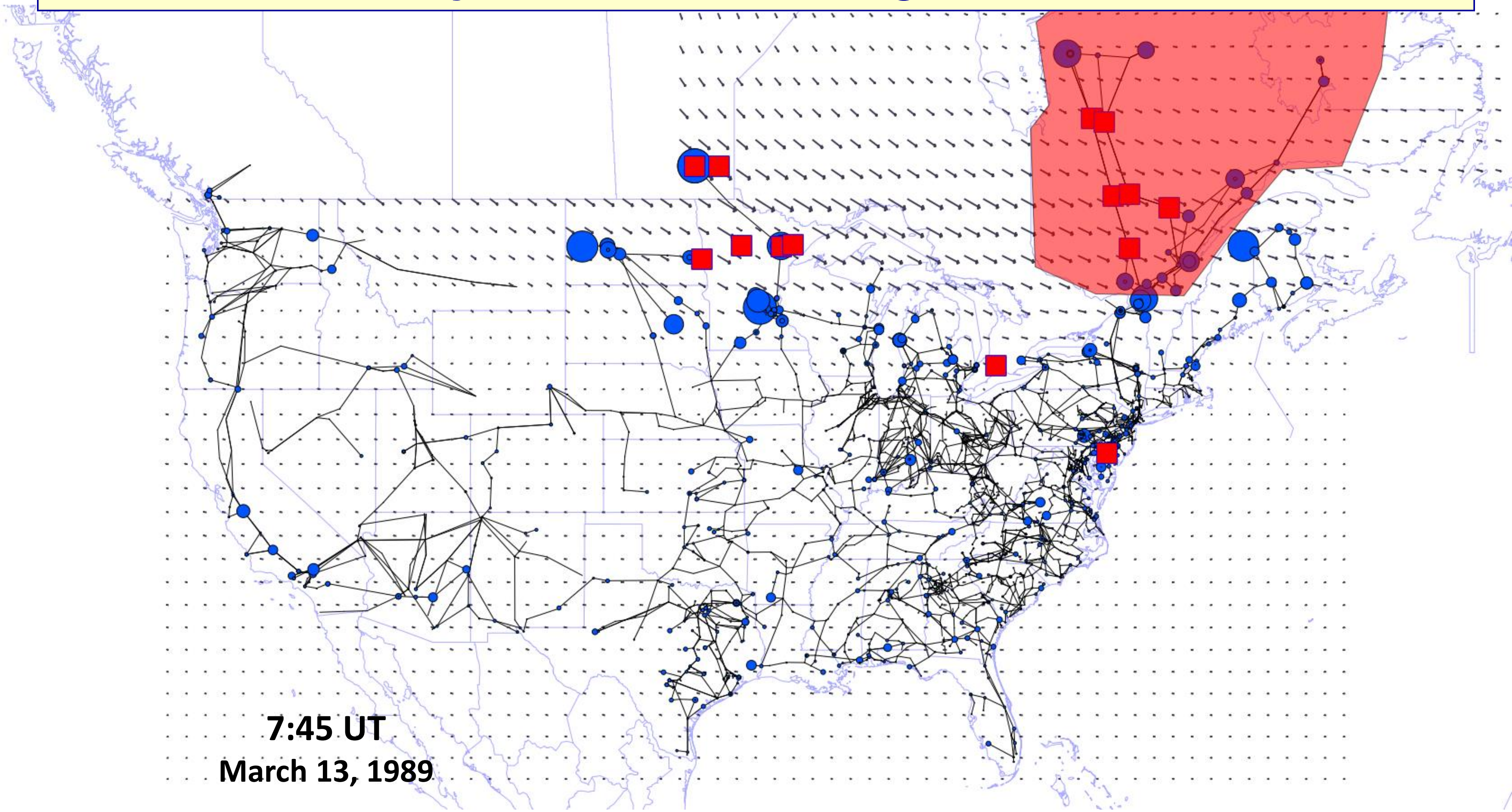
Intensity of Field, Modeling of GIC Flows



Early Substorm which caused Quebec Power Grid Collapse

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows

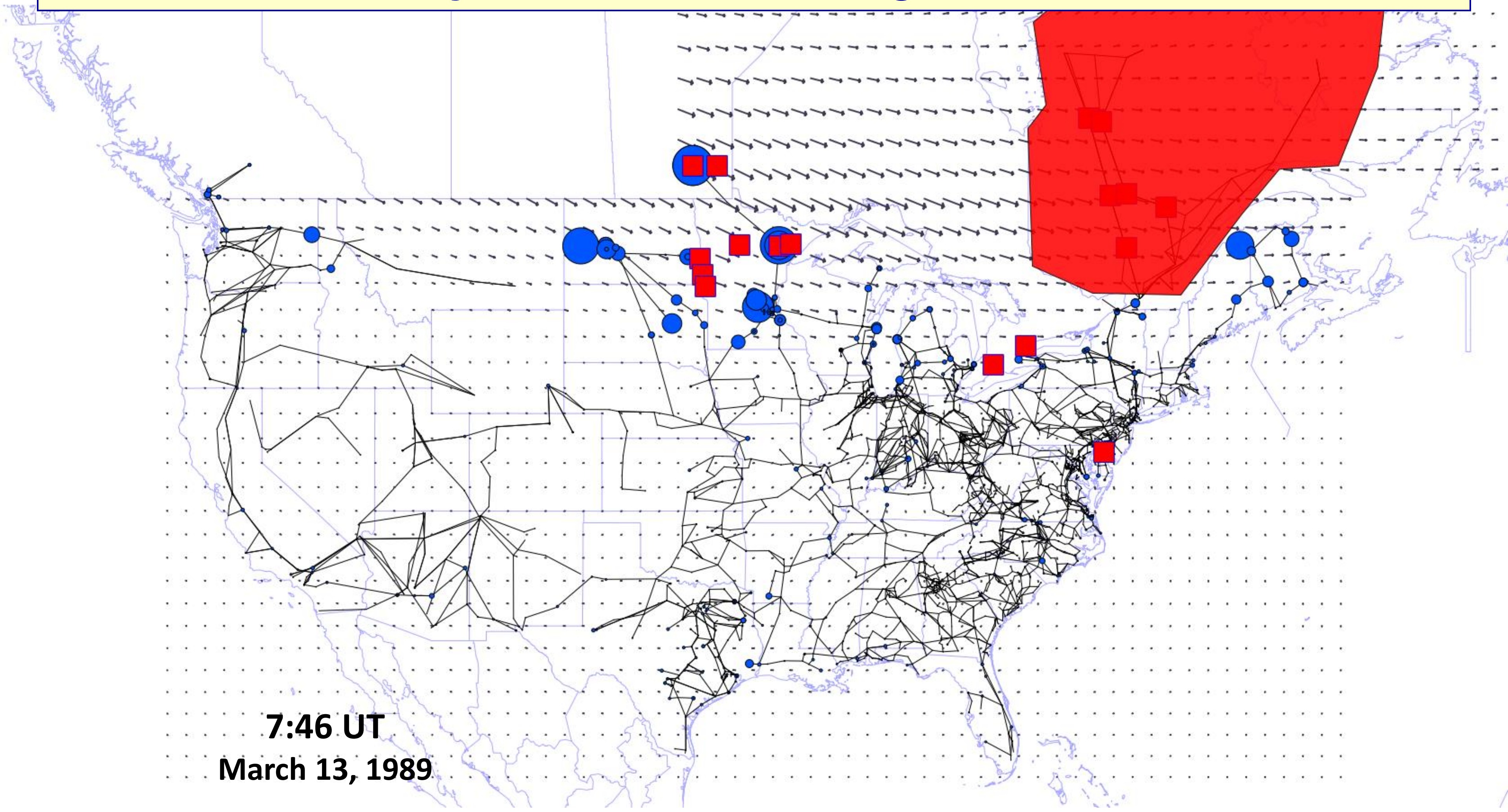


Early Substorm which caused Quebec Power Grid Collapse

Storm Analysis Consultants

Geo-Electric Field & Power Grids

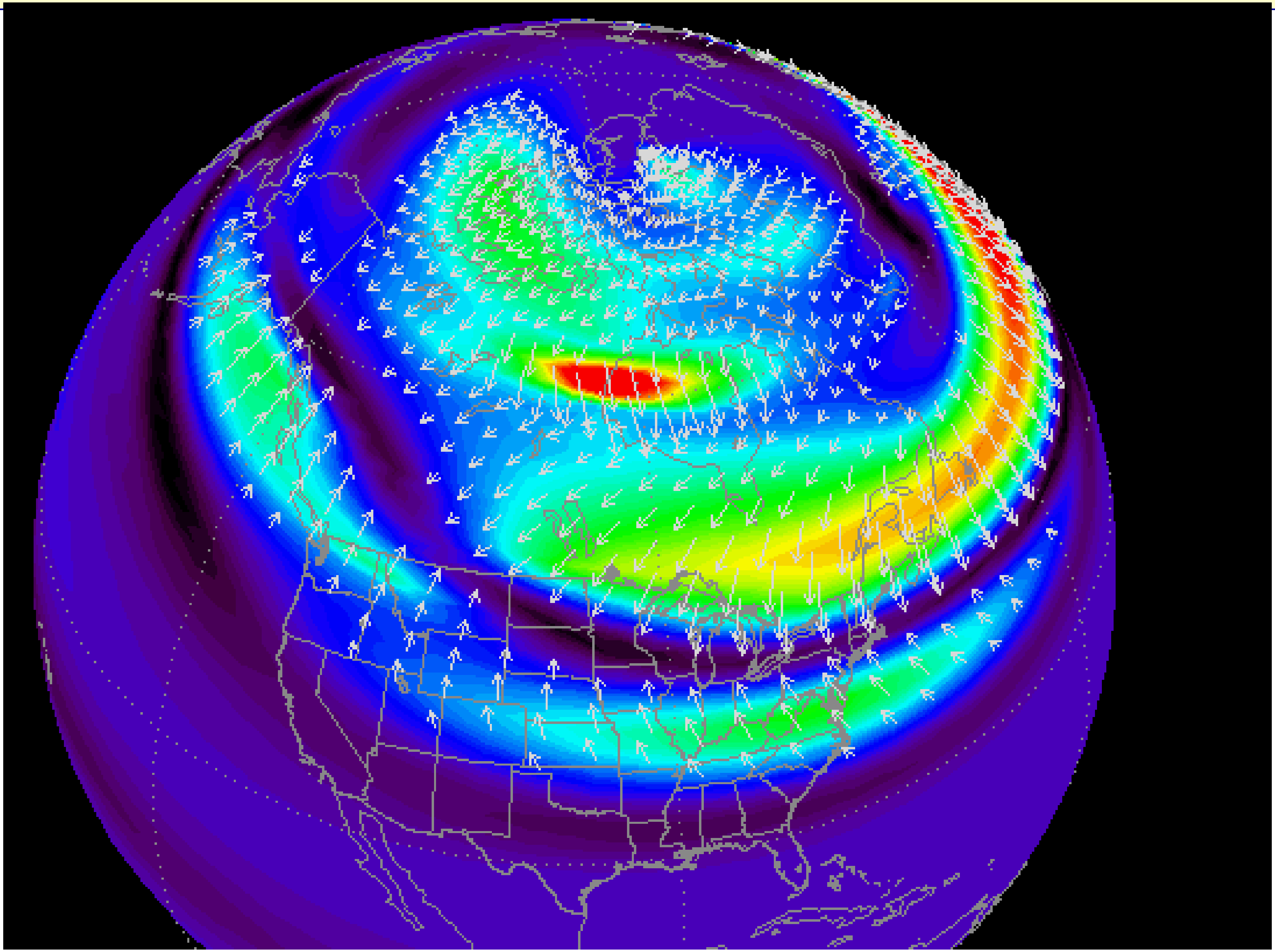
Intensity of Field, Modeling of GIC Flows



Early Substorm which caused Quebec Power Grid Collapse

Storm Analysis Consultants

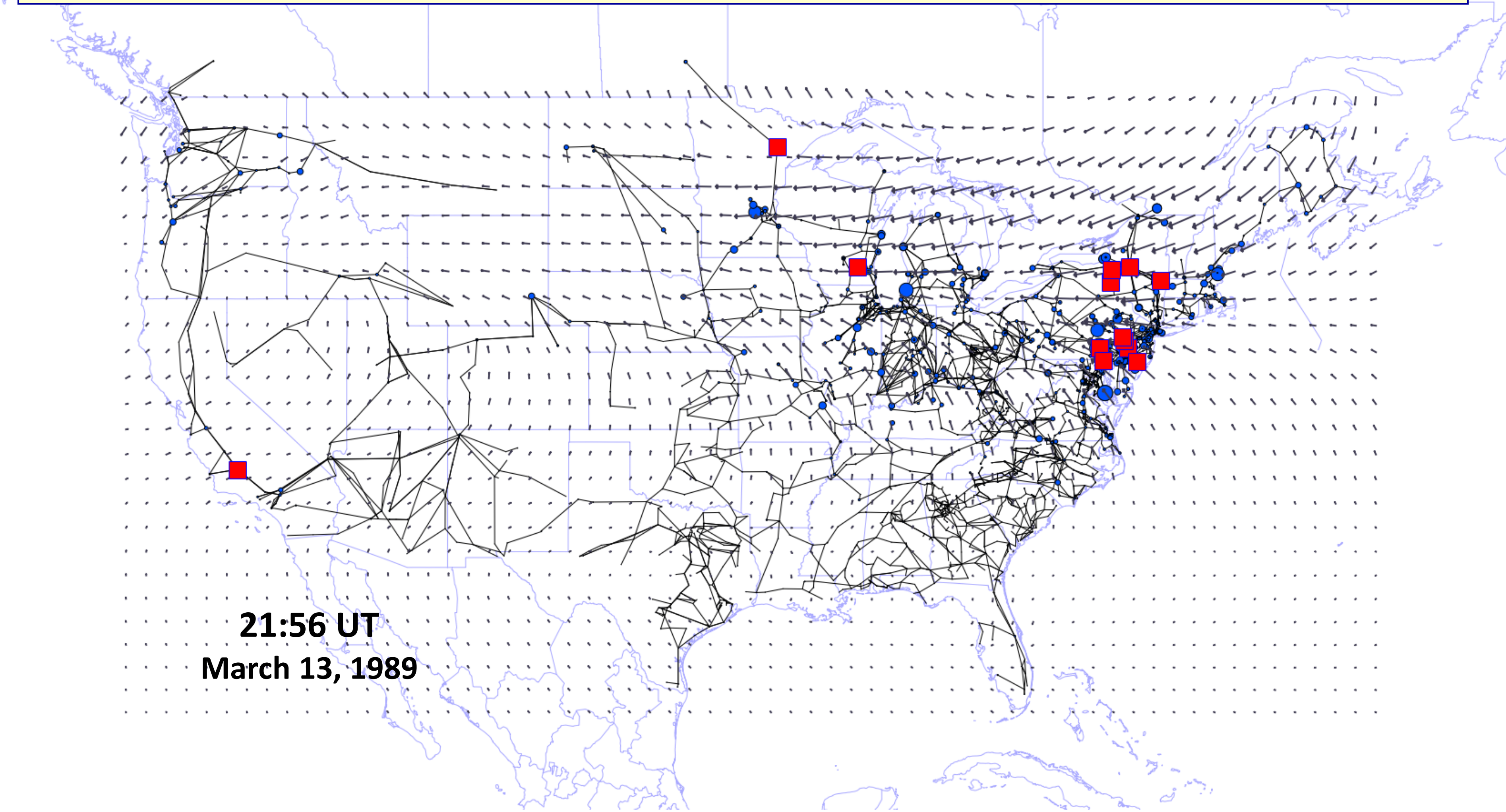
March 13, 1989 – Superstorm @ 4:40 PM (21:40 UT)



Time 4:40-5:30 PM EST (21:40-22:30 UT)

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows

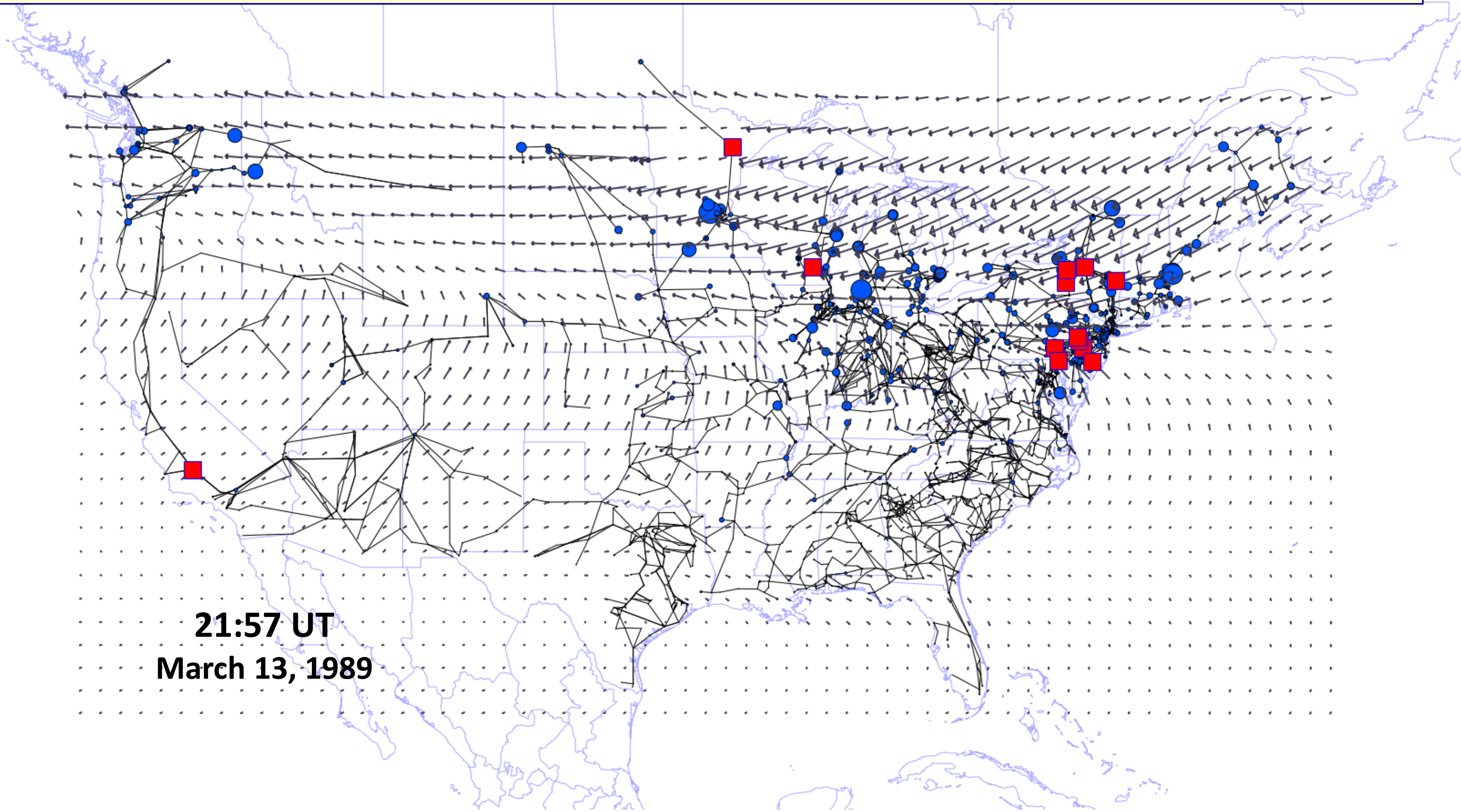


Later Substorm which threatened Broad US Power Grid Collapse

Storm Analysis Consultants

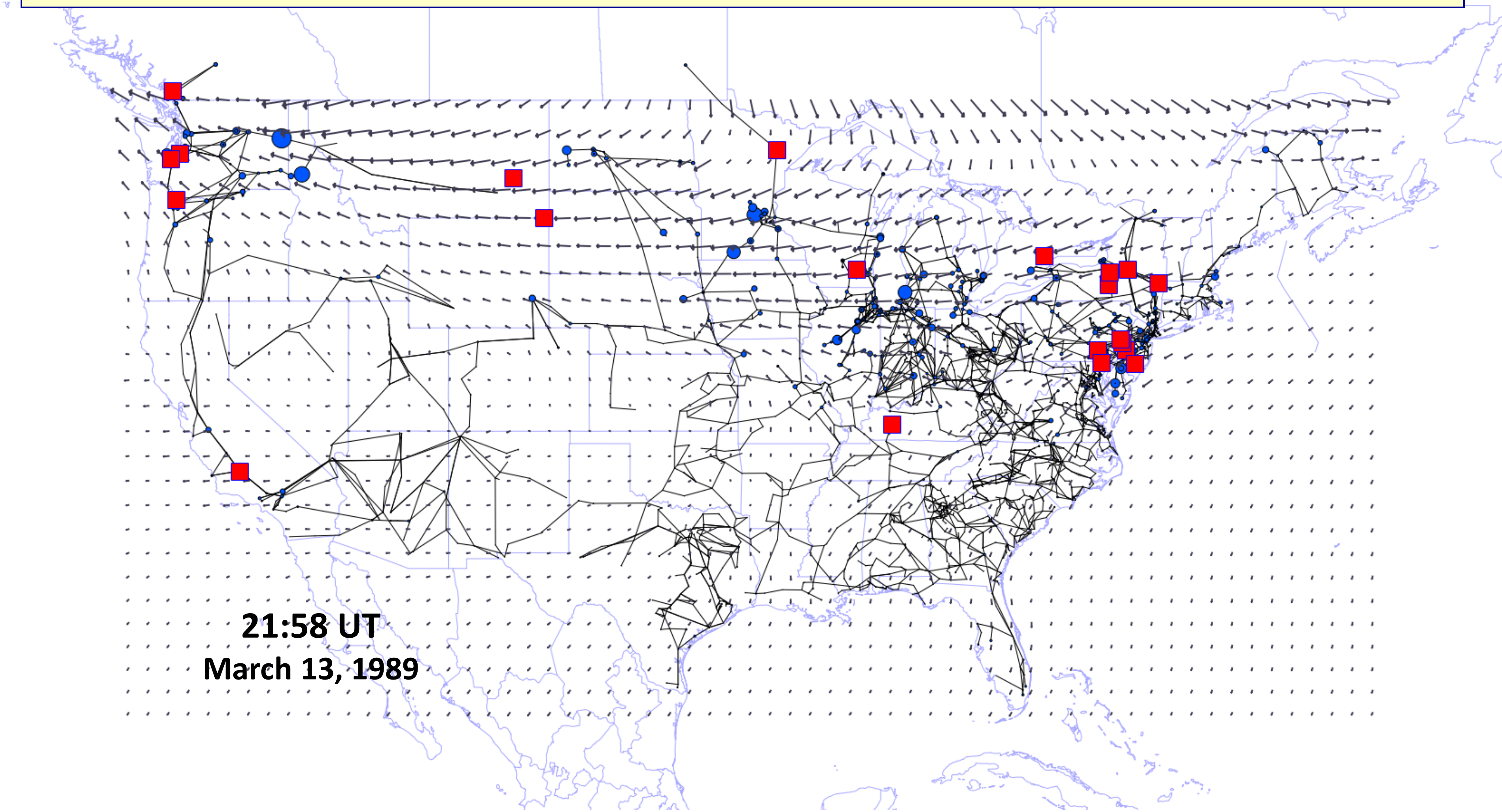
Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows



Later Substorm which threatened Broad US Power Grid Collapse

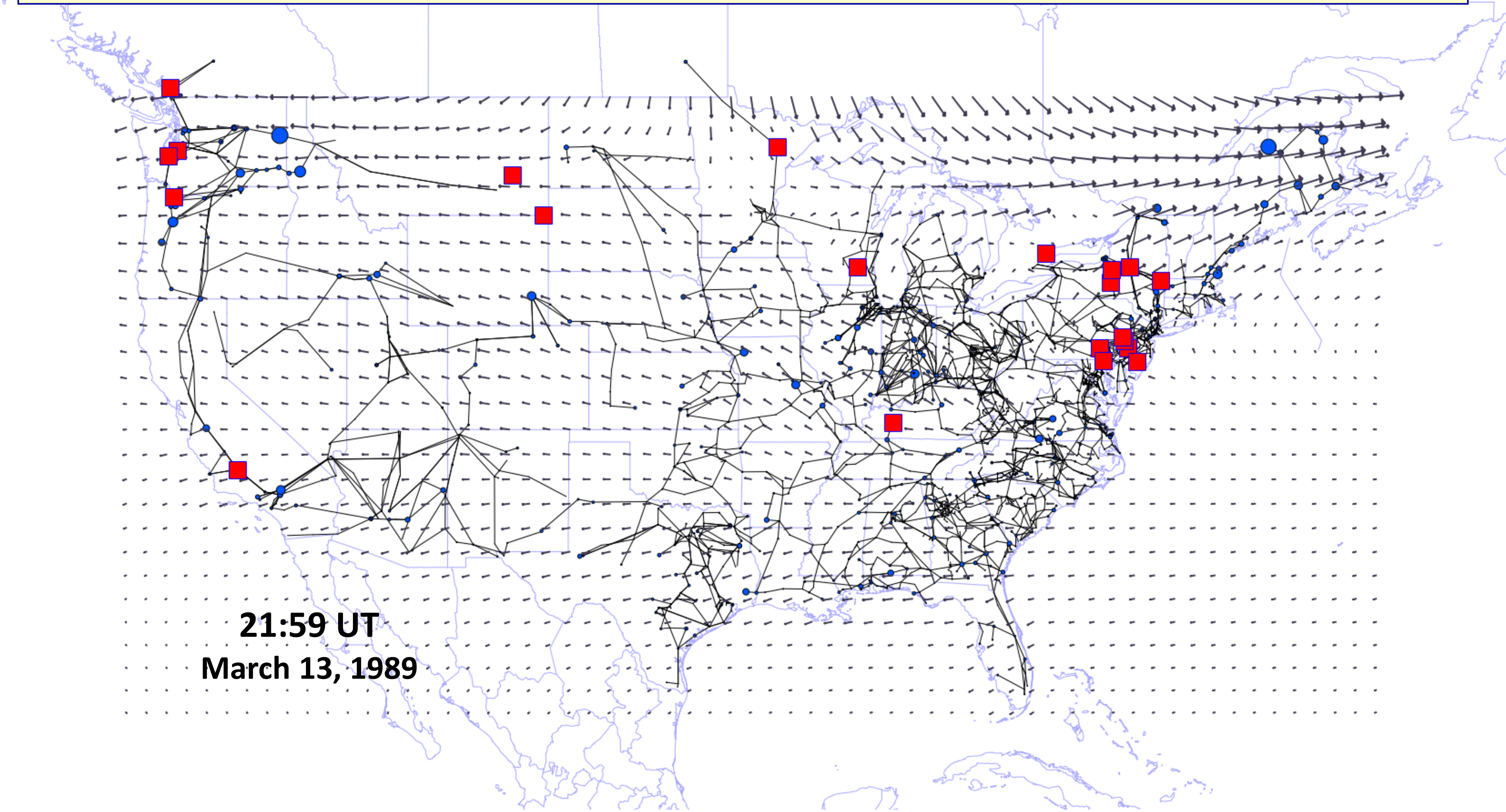
Geo-Electric Field & Power Grids
Intensity of Field, Modeling of GIC Flows



Later Substorm which threatened Broad US Power Grid Collapse

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows

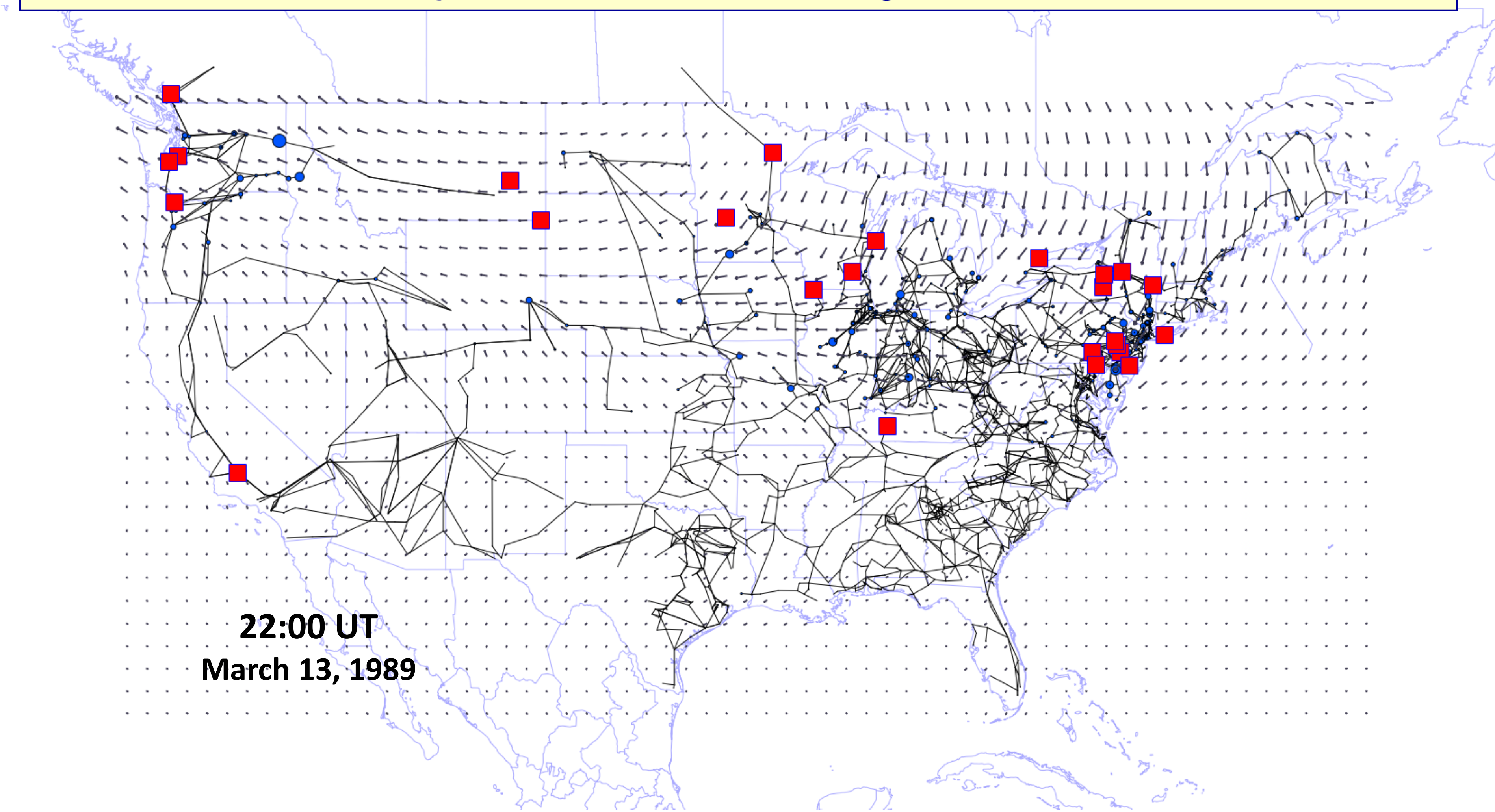


Later Substorm which threatened Broad US Power Grid Collapse

Storm Analysis Consultants

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows

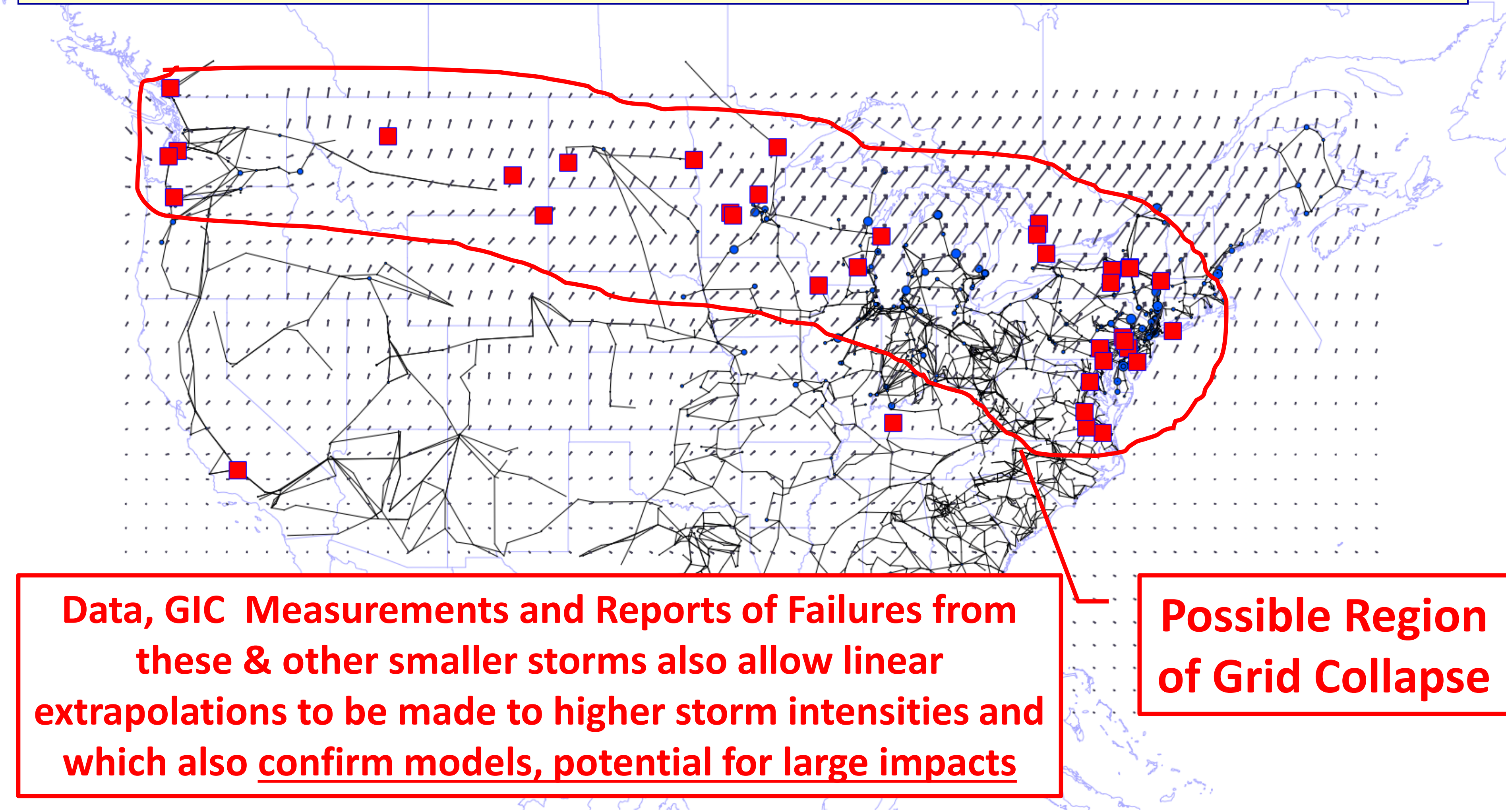


Later Substorm which threatened Broad US Power Grid Collapse

Storm Analysis Consultants

Geo-Electric Field & Power Grids

Intensity of Field, Modeling of GIC Flows



Data, GIC Measurements and Reports of Failures from these & other smaller storms also allow linear extrapolations to be made to higher storm intensities and which also <u>confirm models, potential for large impacts</u>

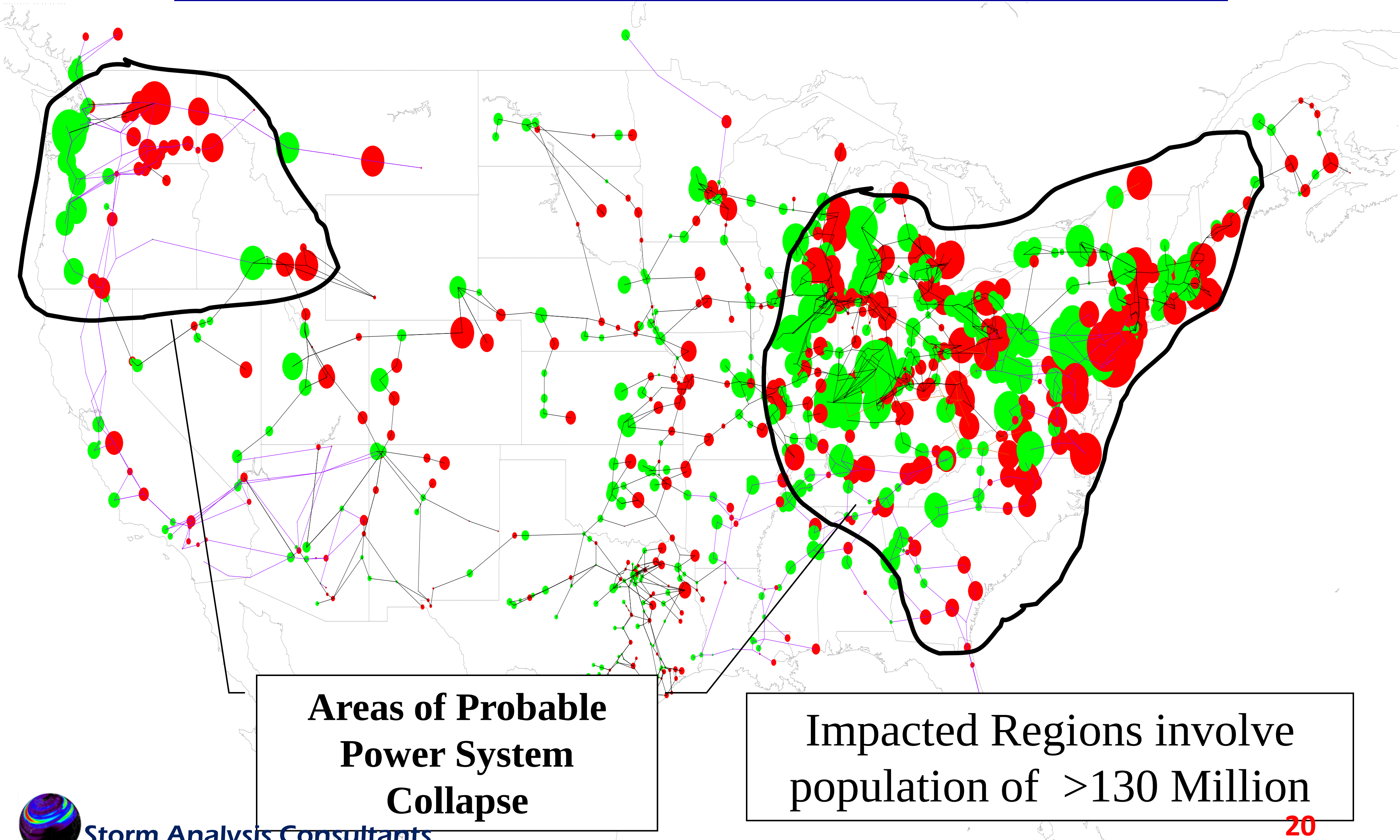
Possible Region of Grid Collapse

Later Substorm which threatened Broad US Power Grid Collapse

Storm Analysis Consultants

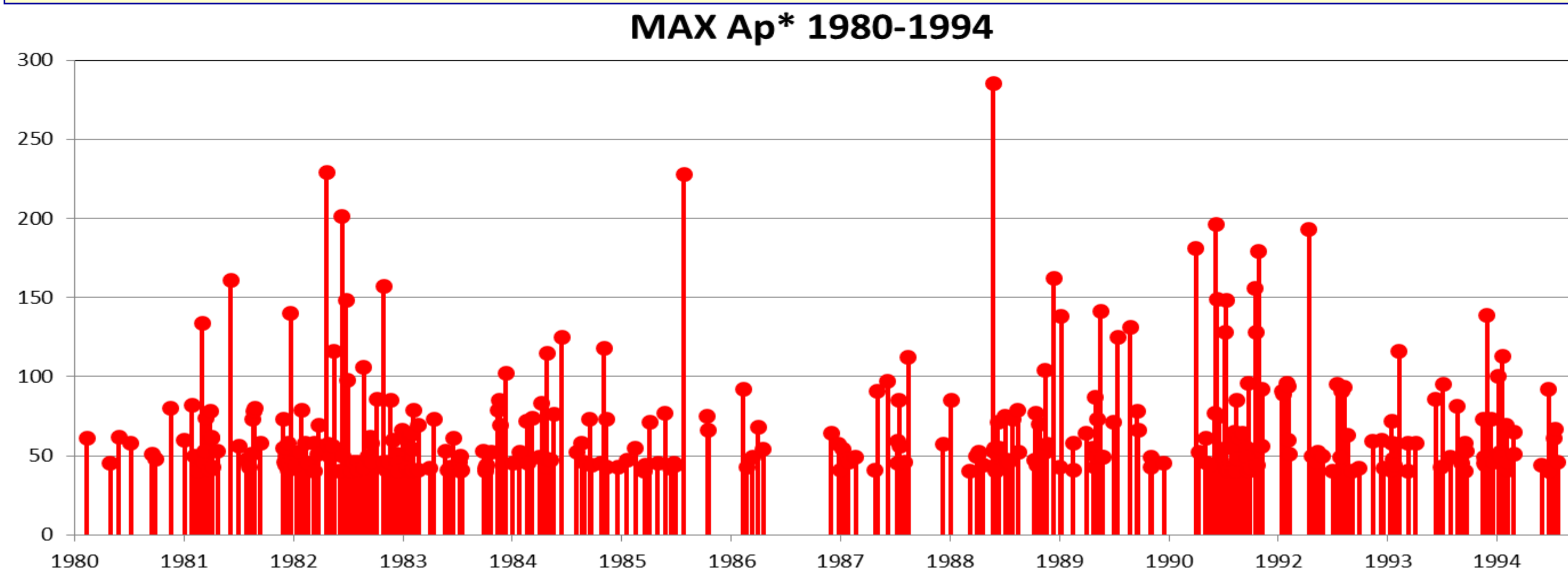
Severe Geomagnetic Storm Disturbance Scenario

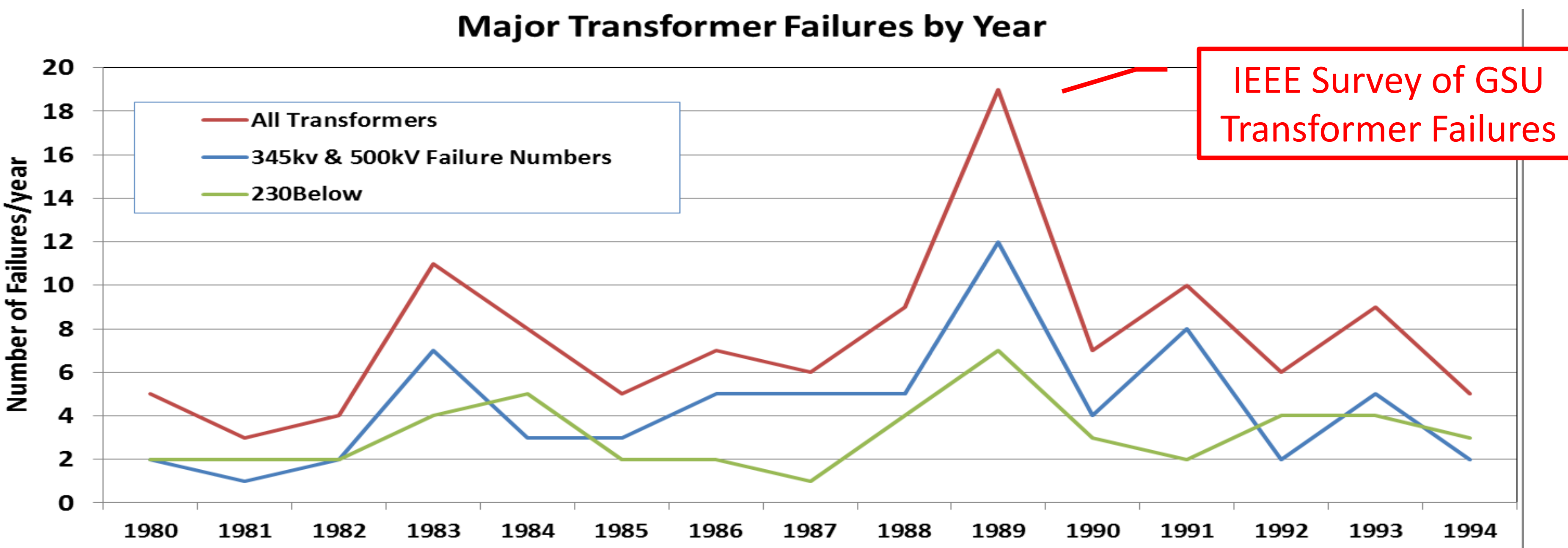
Power System Disturbance and Outage Scenario of Unprecedented Scale



Storm Analysis Consultants

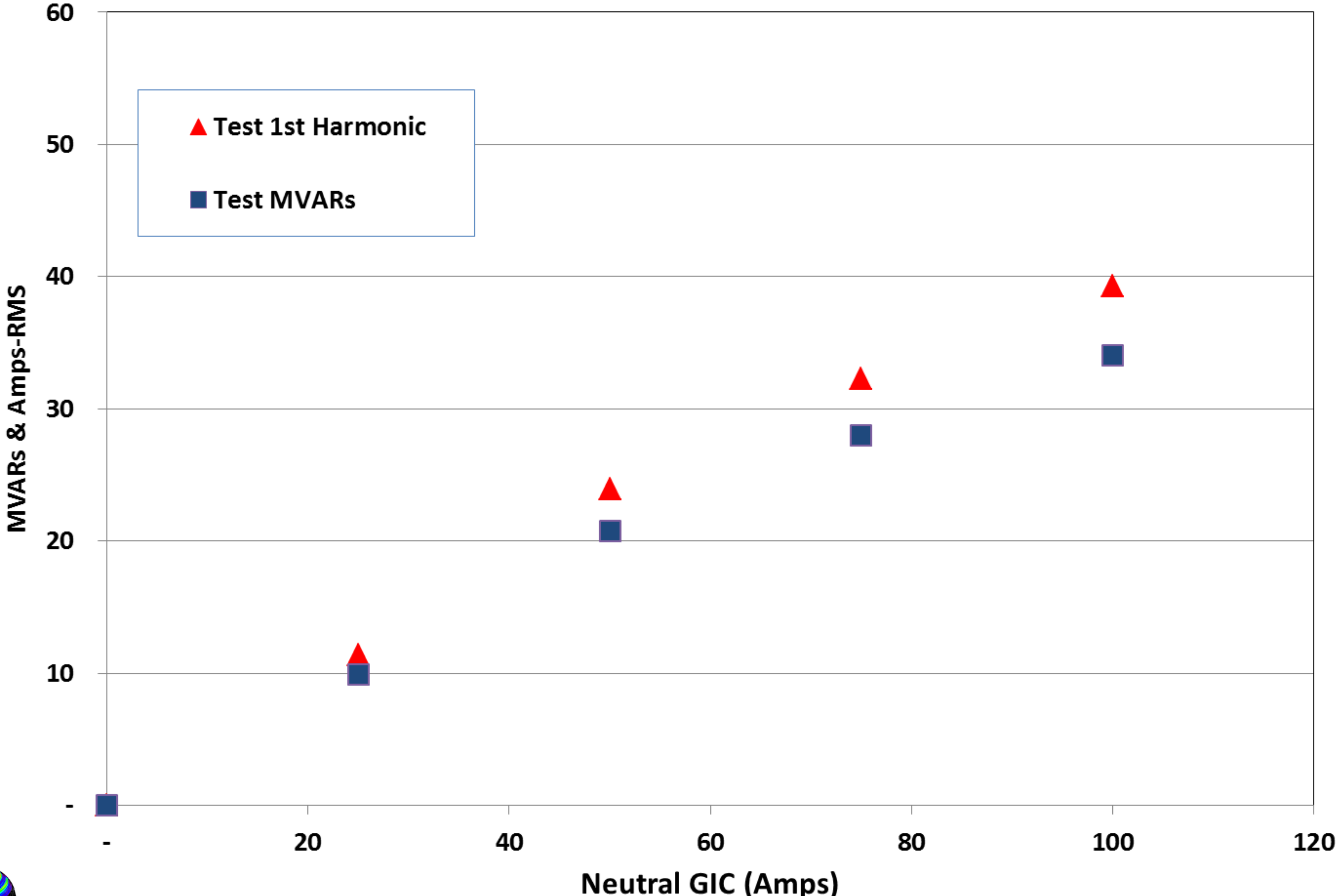
Geomagnetic Storms & Transformer Failures – Historic Trends



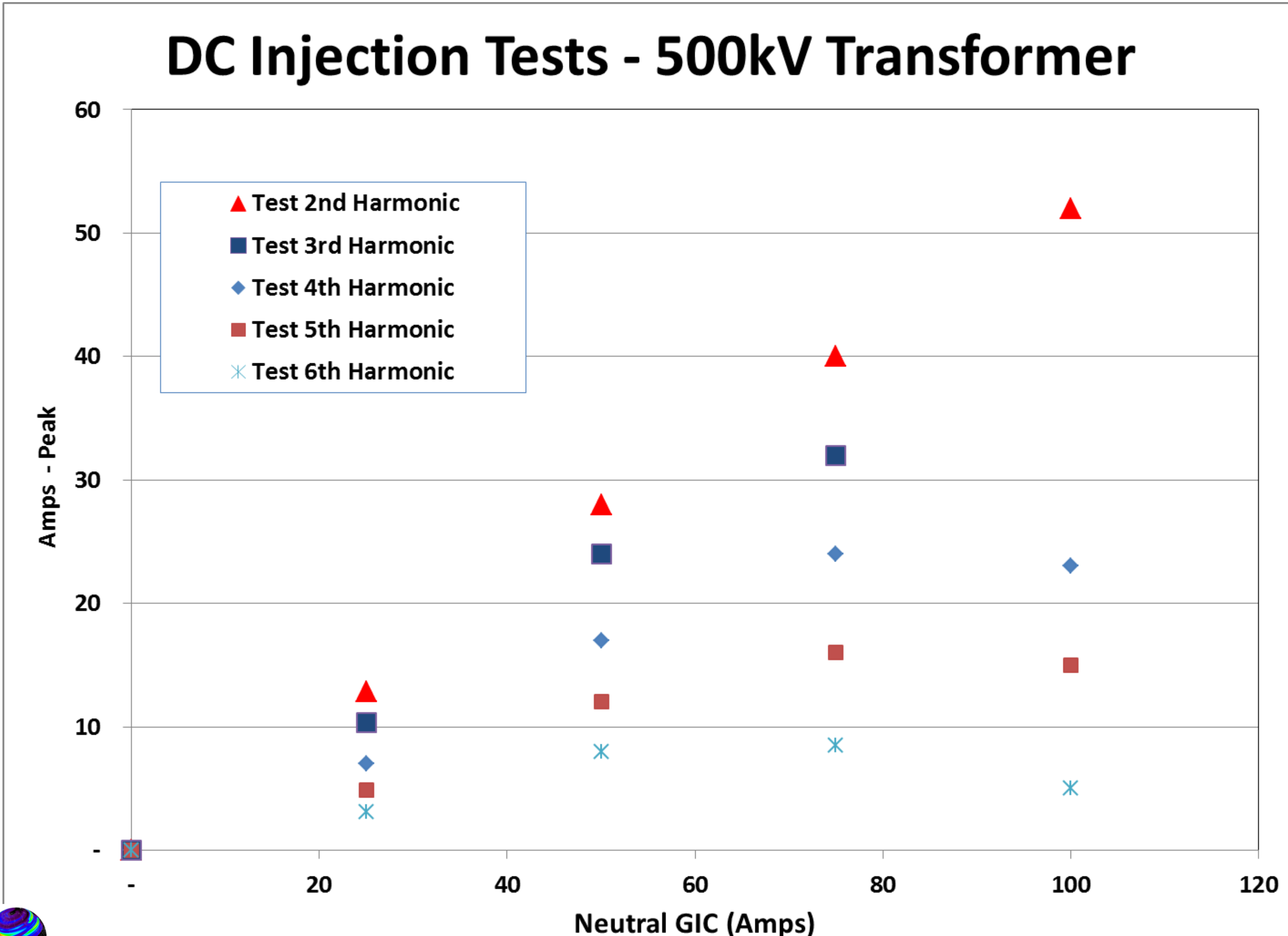


DC Injection Tests on 500kV Transformers

DC Injection Tests - 500kV Transformer

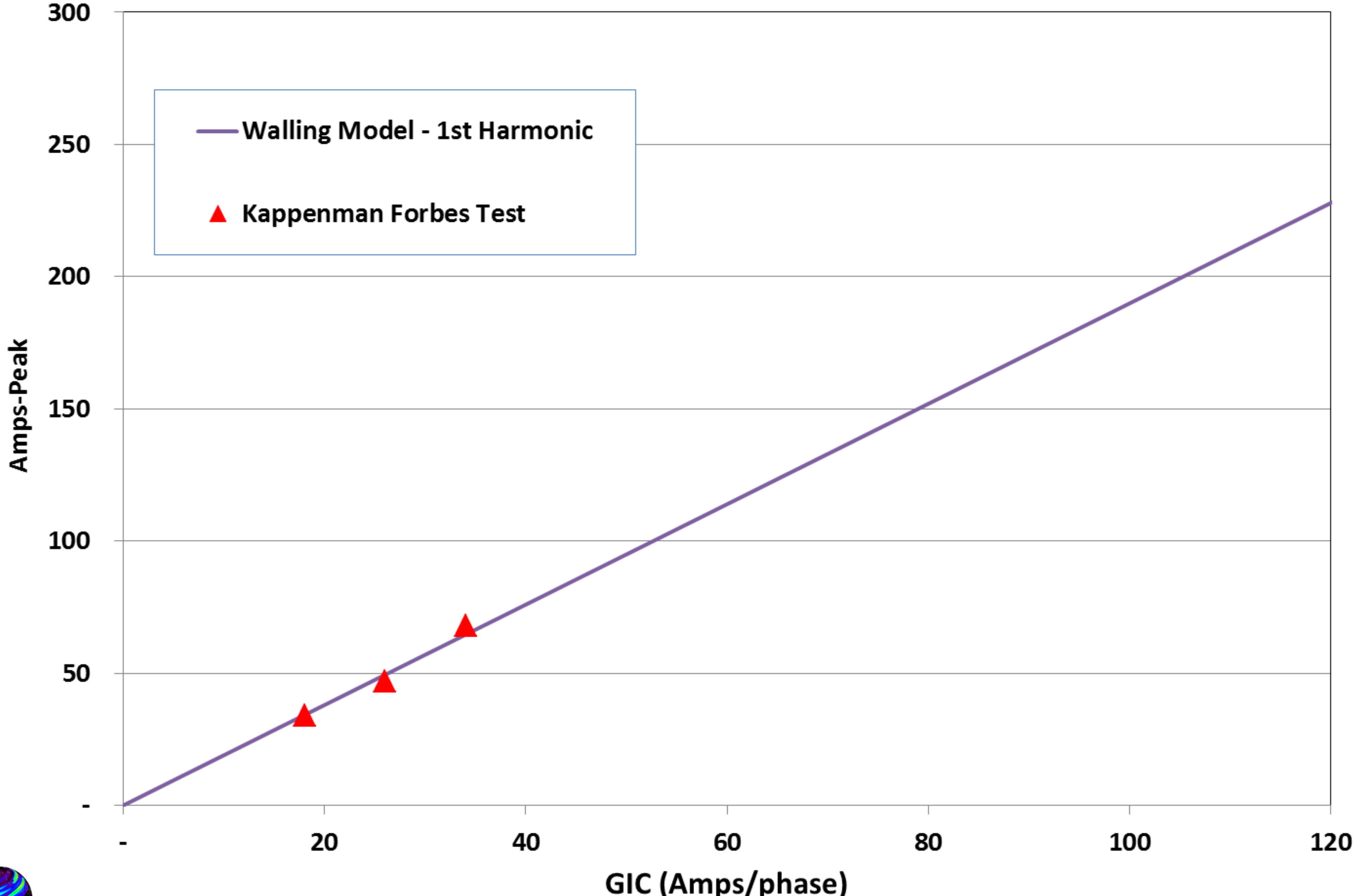


Storm Analysis Consultants

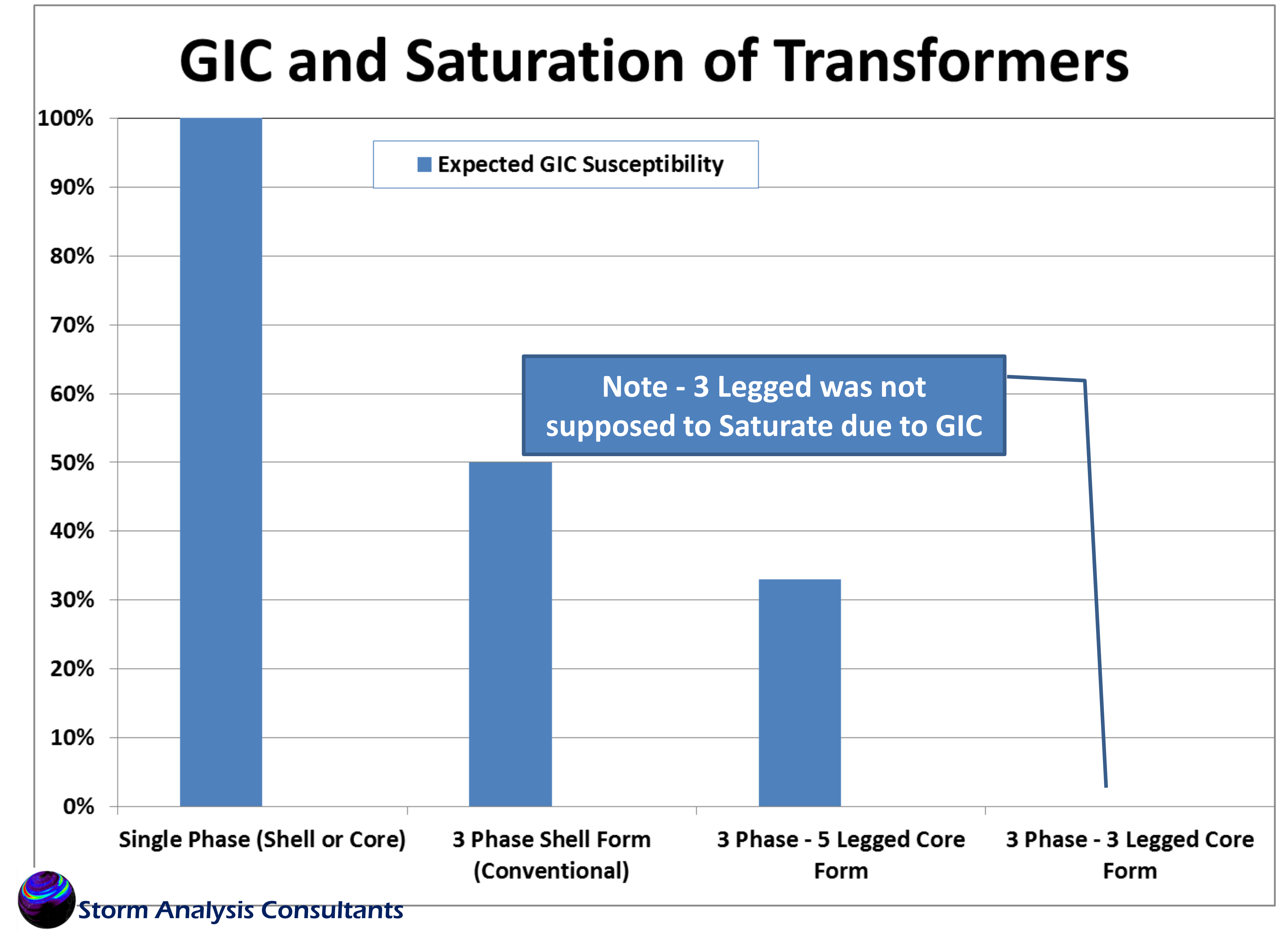


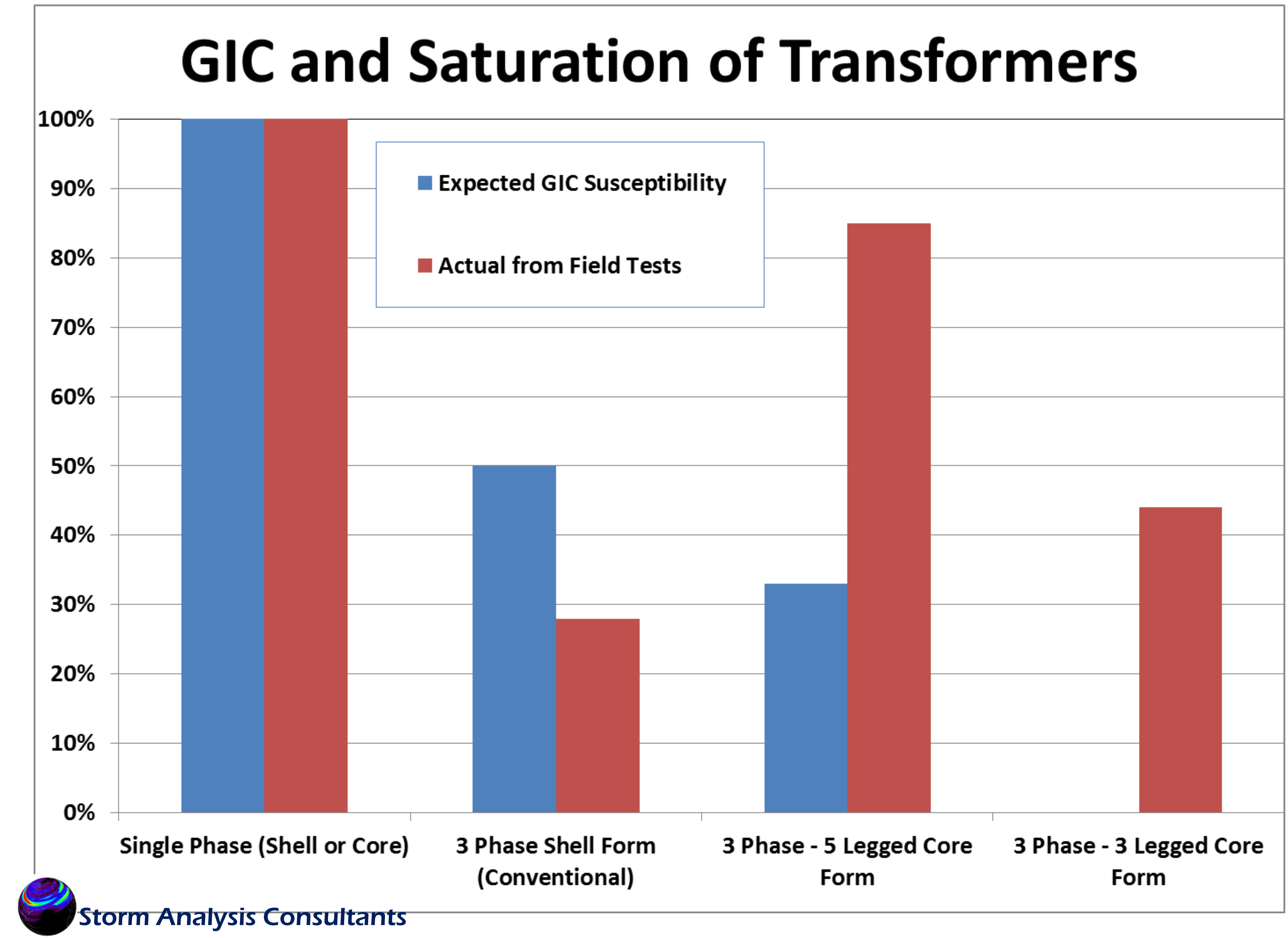
Storm Analysis Consultants

DC Injection Tests - 500kV Transformer



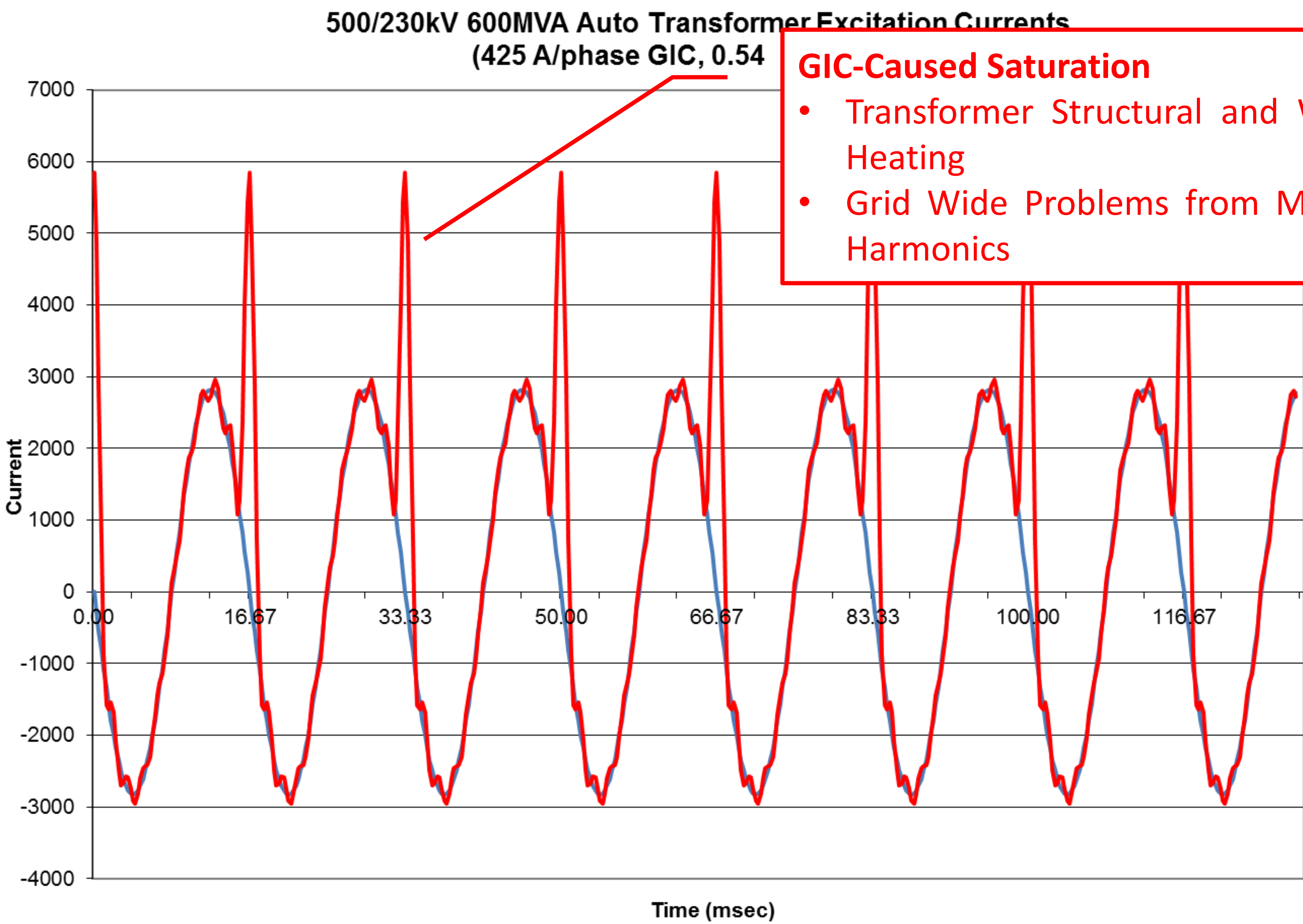
Storm Analysis Consultants


GIC and Saturation of Transformers
Expected GIC Susceptibility
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Note - 3 Legged was not supposed to Saturate due to GIC
Single Phase (Shell or Core)
3 Phase Shell Form (Conventional)
3 Phase - 5 Legged Core Form
3 Phase - 3 Legged Core Form
Storm Analysis Consultants



GIC and Saturation of Transformers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Expected GIC Susceptibility
Actual from Field Tests
Single Phase (Shell or Core)
3 Phase Shell Form (Conventional)
3 Phase - 5 Legged Core Form
3 Phase - 3 Legged Core Form
Storm Analysis Consultants

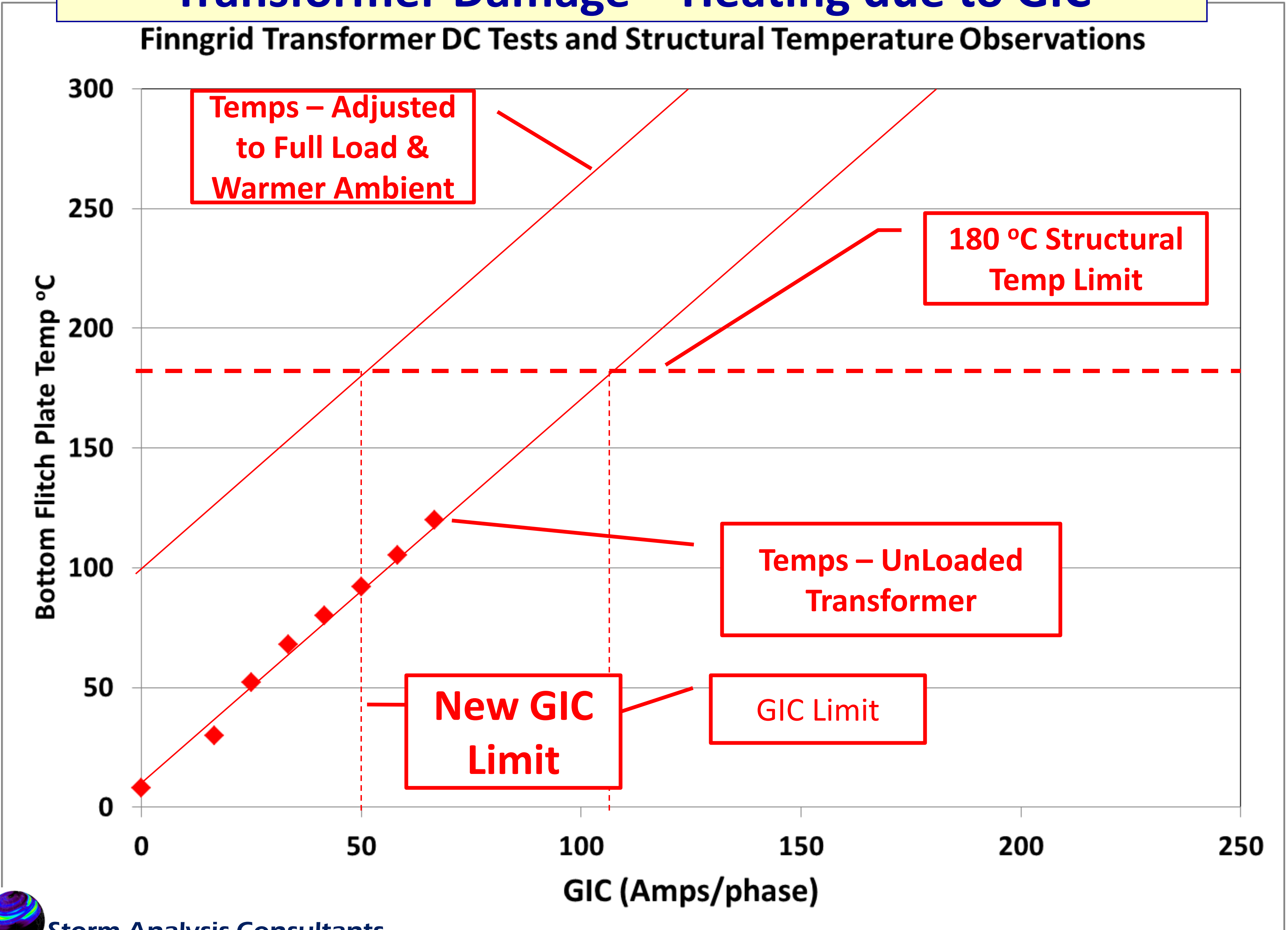
Transformer Damage – Heating due to GIC



GIC-Caused Saturation

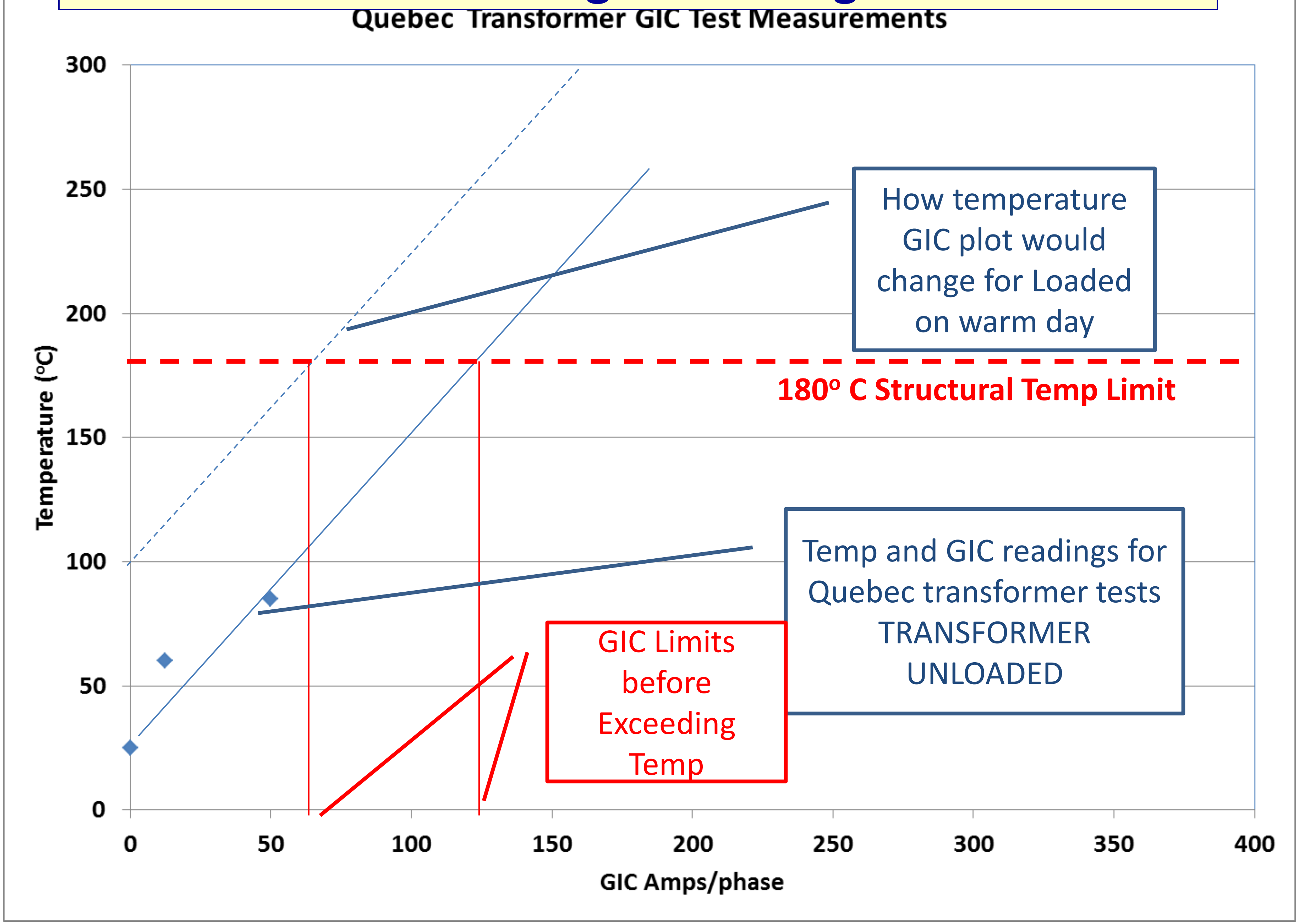
- Transformer Structural and Winding Heating
- Grid Wide Problems from MVARs & Harmonics

Transformer Damage – Heating due to GIC



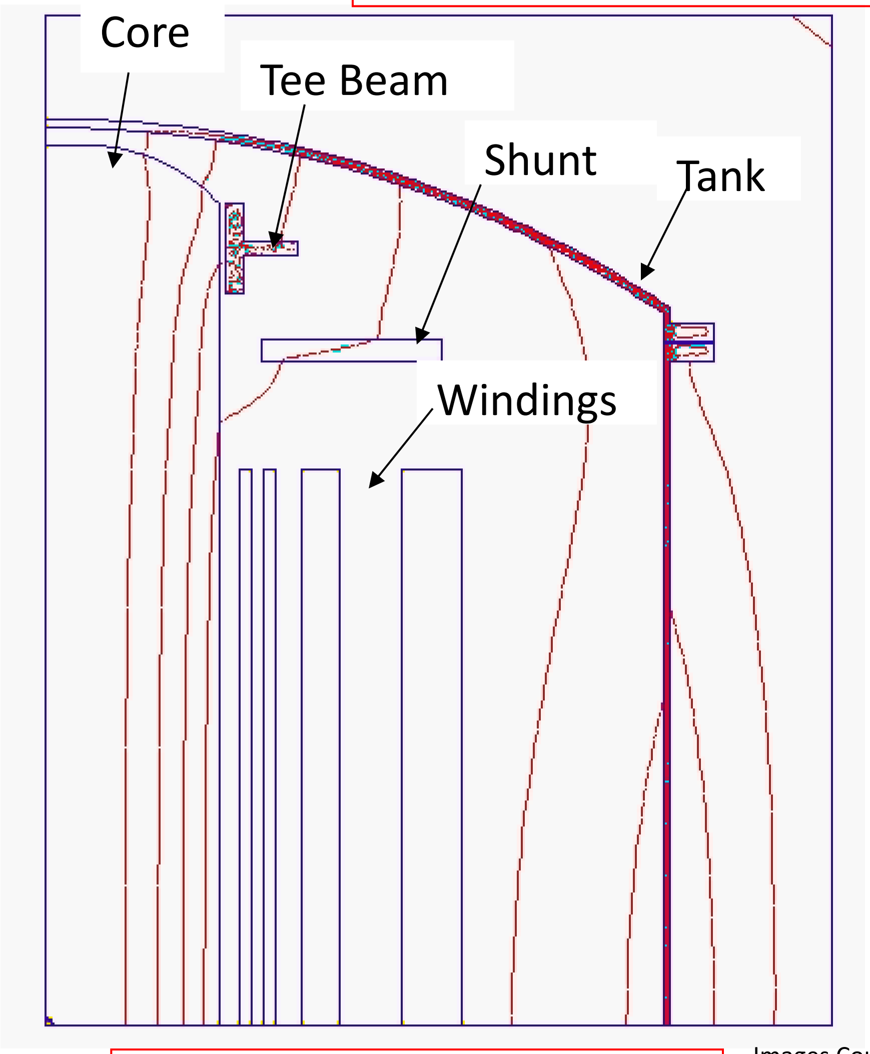
Storm Analysis Consultants

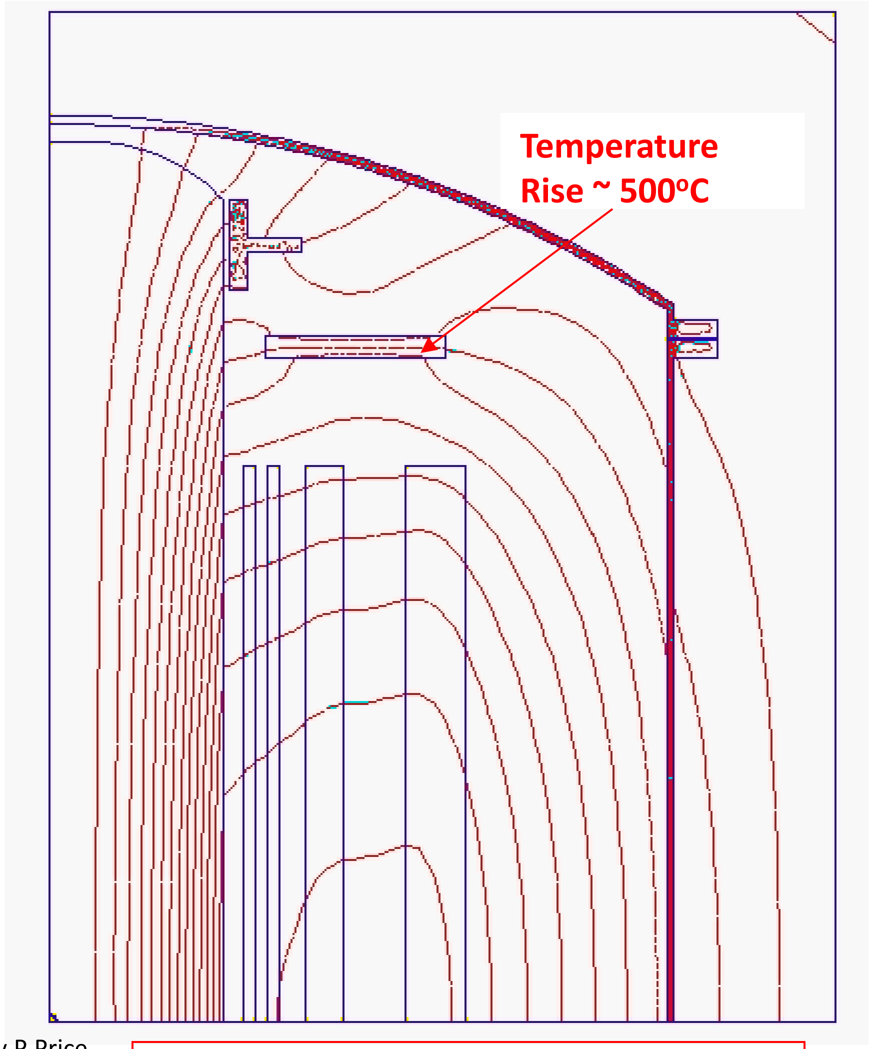
Transformer Damage – Heating due to GIC



Transformer Simulations Provide a View into Problems in Non-Core Regions

Flux Distribution in Transformer over a 60 Hz Cycle





Flux Distribution at Min Flux

Images Courtesy P.Price

Flux Distribution at Peak Flux

Source – P. Price - IEEE

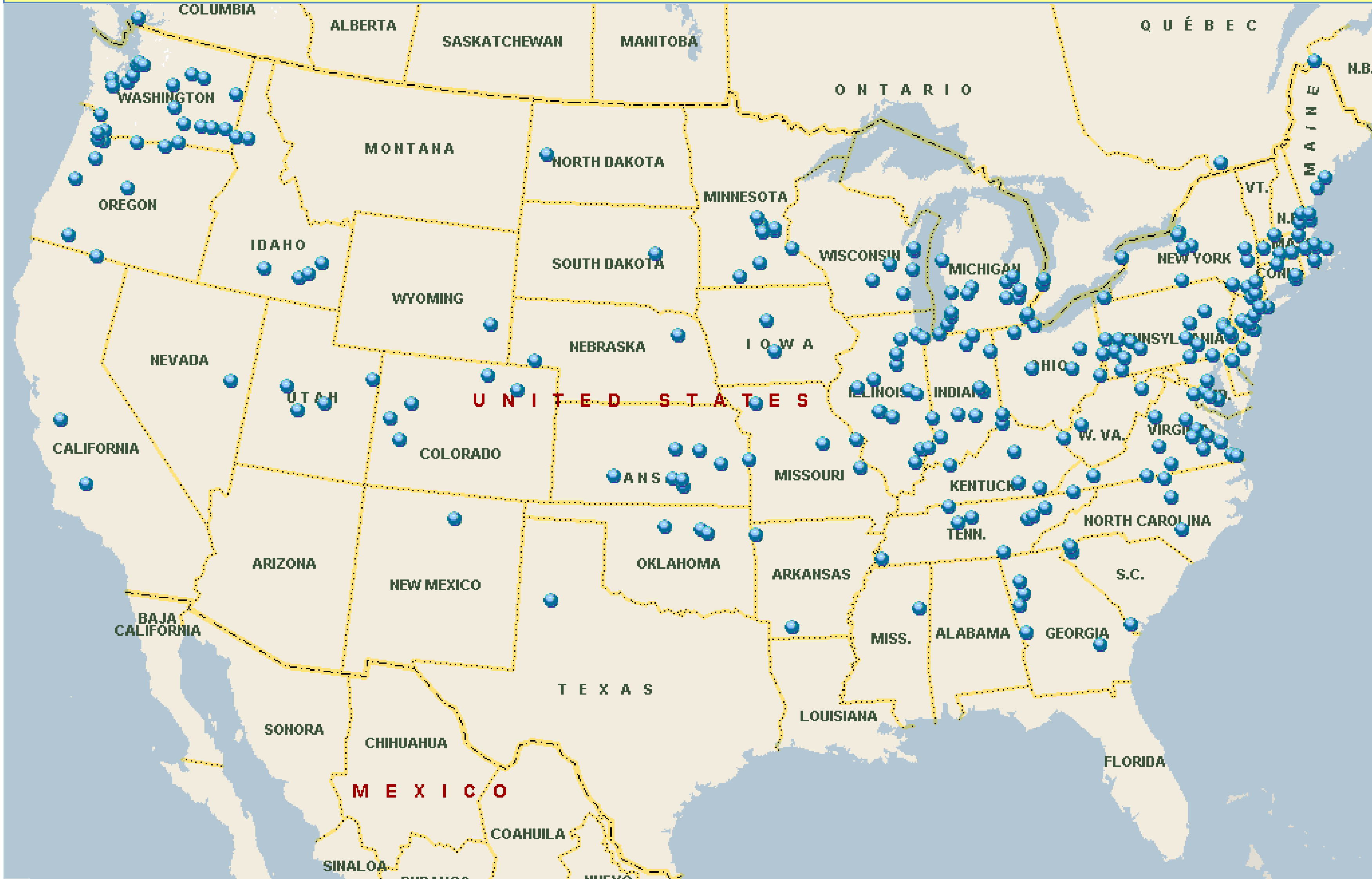
Price – Transformer GIC Limits

Transformer Core Type, three phase with separate delta and steel tank	GIC Current amperes/phase.				
	5	10	25	50	100
3 limb no core bolts.	Non	Lo.	Lo.	Lo.	Pos.
3 Limb + core bolts in limbs & yokes.	Lo.	Lo.	Lo.	Lo.	Pos.
5 limb no core bolts in yokes or limbs.	Lo.	Lo.	Lo.	Pos.	Hi.
5 limb + core bolts in yokes & limbs.	Lo.	Pos.	Pos.	Pos.	Hi.
3 off bank single phase, no core bolts yokes or limbs.	Lo.	Lo.	Pos.	Pos.	Hi
3 off bank single phase + core bolts in main and return limbs.	Lo.	Pos.	Hi.	Hi.	Hi.

Typical of EHV Transformer Design in US

Location of At-Risk Transformers

4800 nT/min at 50º (GIC > 90 Amps/phase)



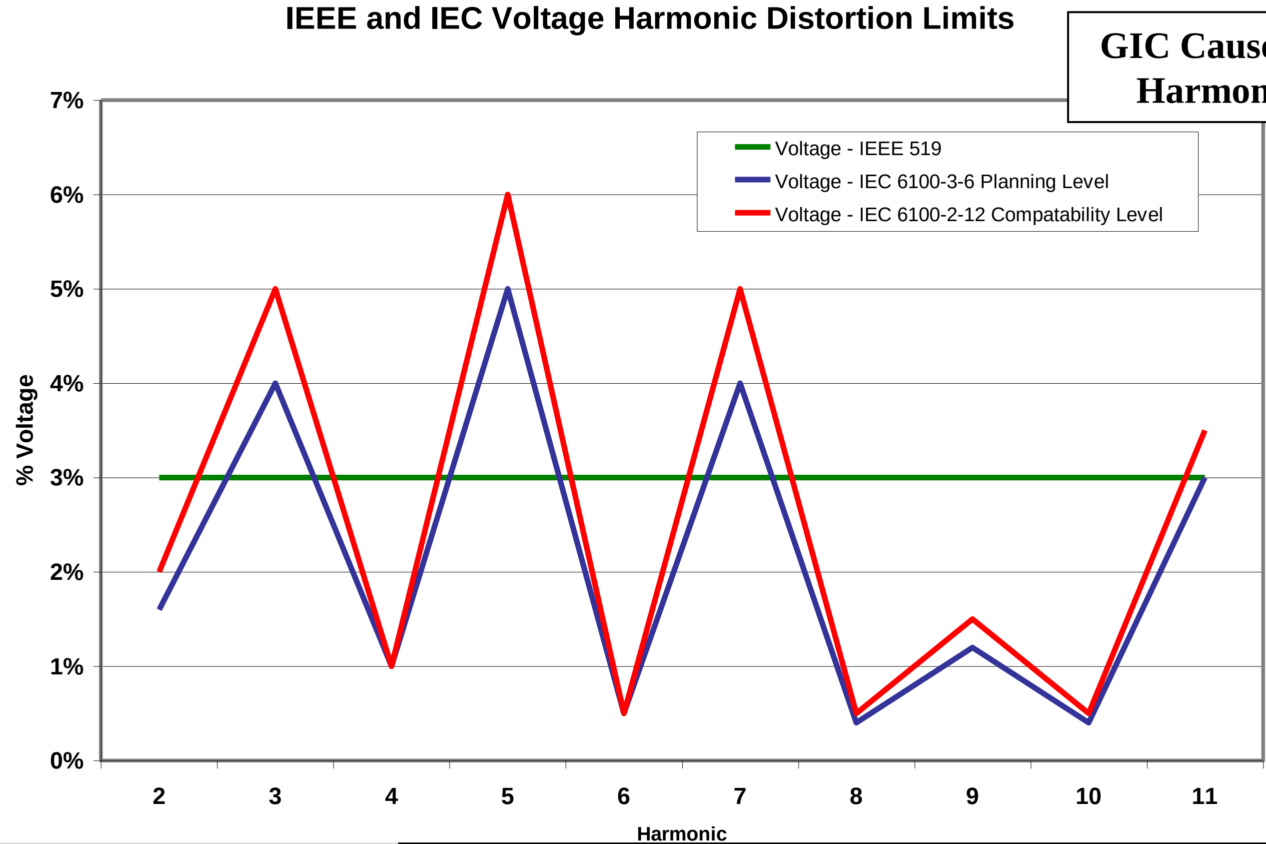
Storm Analysis Consultants

Generators At-Risk (50 A/ph or greater) 4800 nT/min Threat Level

Ave GIC - 151 A/phase

IEC Equipment Immunity Levels and Test Methods

GIC Causes Both Even & Odd Harmonics at High Levels



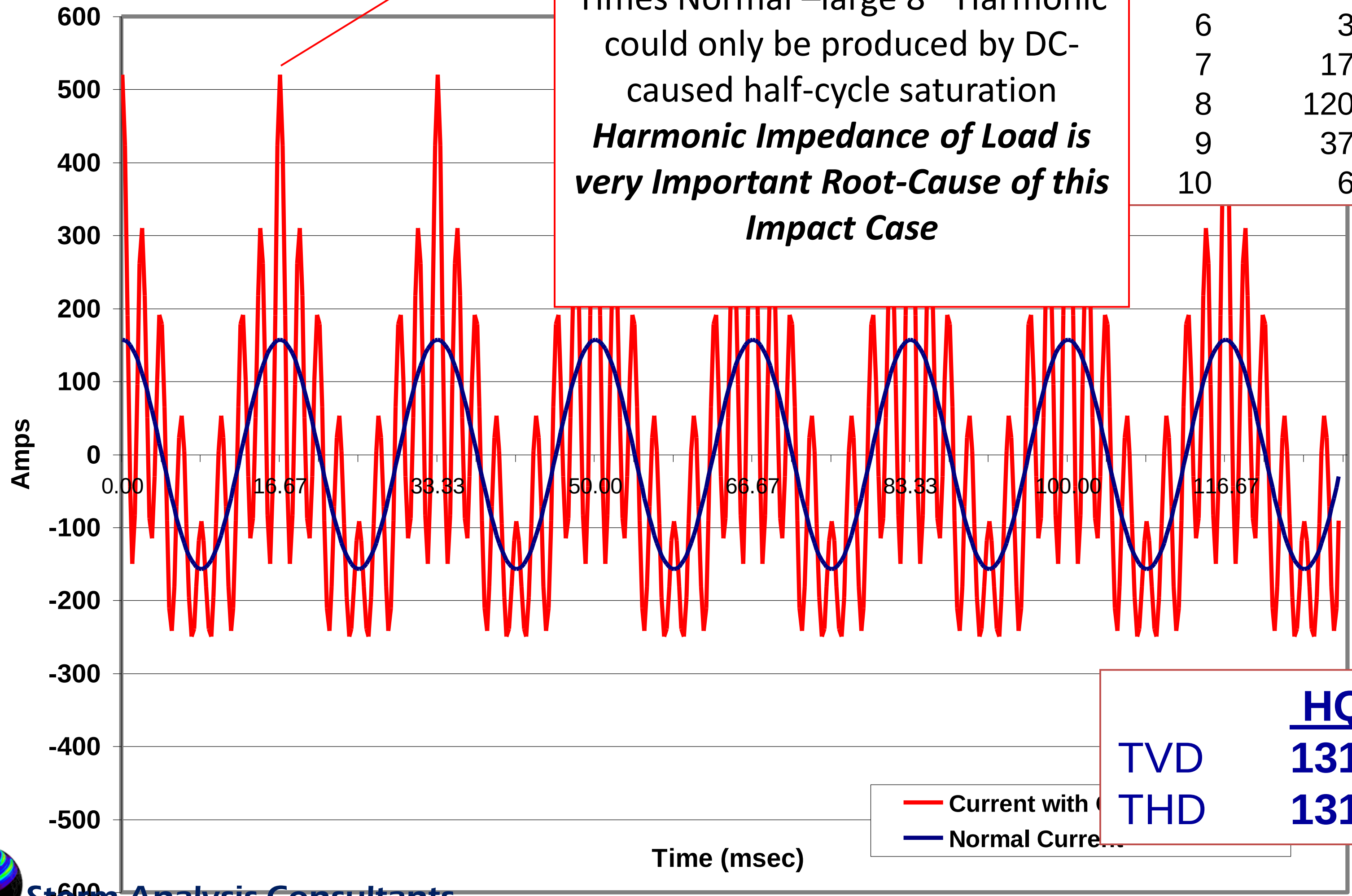
	THD	2nd	3rd	4th	5th	6th	7th	8th	9th
Harmonic Compatibility Levels	8.0%	2.0%	5.0%	1.0%	6.0%	0.5%	5.0%	0.5%	0.5%
Equipment Immunity Levels	16.0%	4.0%	10.0%	2.0%	12.0%	1.0%	10.0%	1.0%	1.0%
per Standard IEC 61000-2-2									

Notice Even Harmonics are Much Lower than Odd Harmonics

Case Studies - Fuse Operation on 60kVAR power factor correction capacitor bank

Estimated Phase B Current Reported @ 18:47 due to GIC

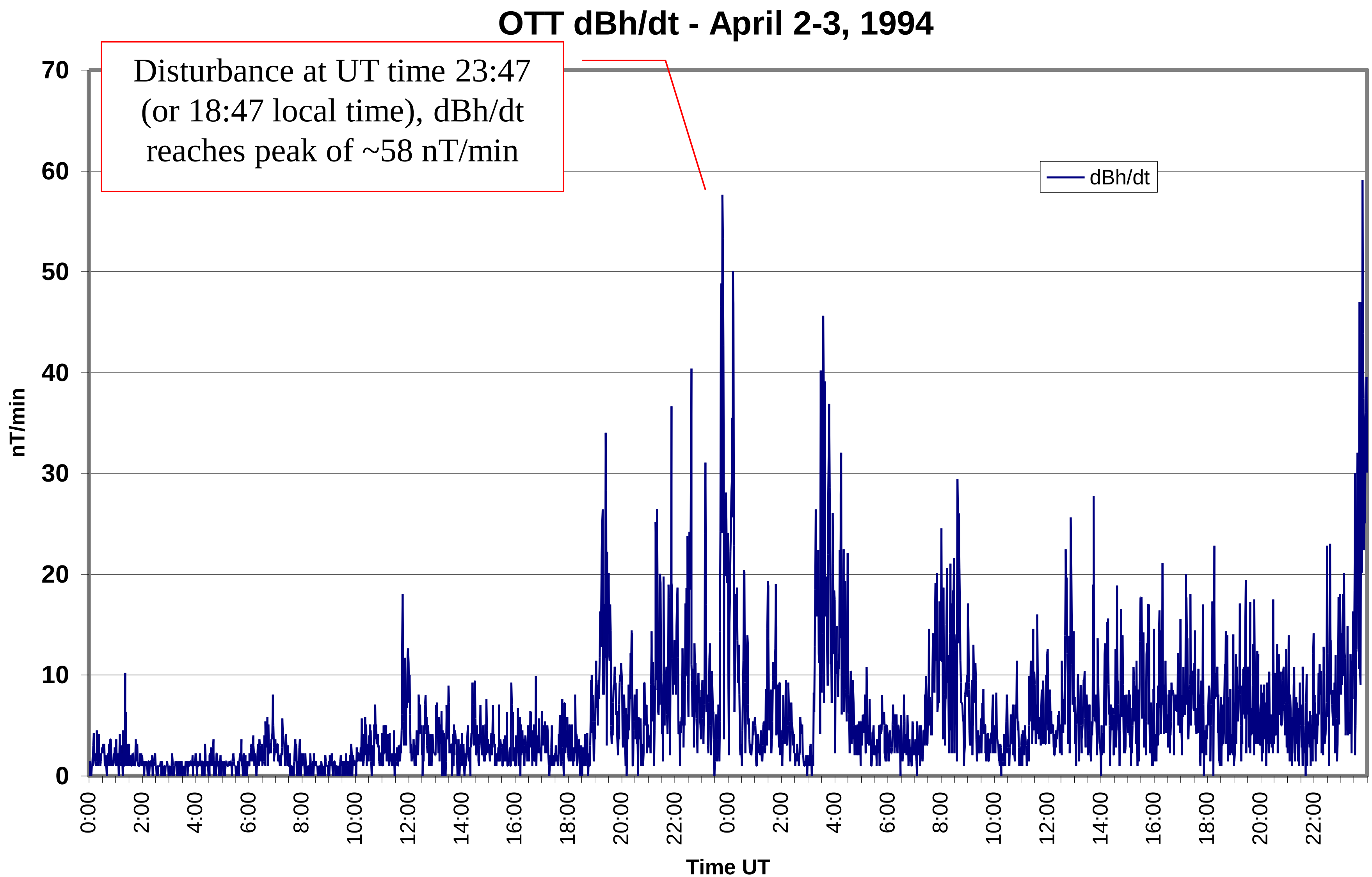
Harmonic	Cap Bank I	Cap Bank V
1	100.0%	100.0%
2	1.0%	0.5%
3	7.2%	0.3%
4	4.7%	0.9%
5	32.3%	2.5%
6	3.6%	0.0%
7	17.9%	1.0%
8	120.4%	6.6%
9	37.3%	1.3%
10	6.9%	0.5%



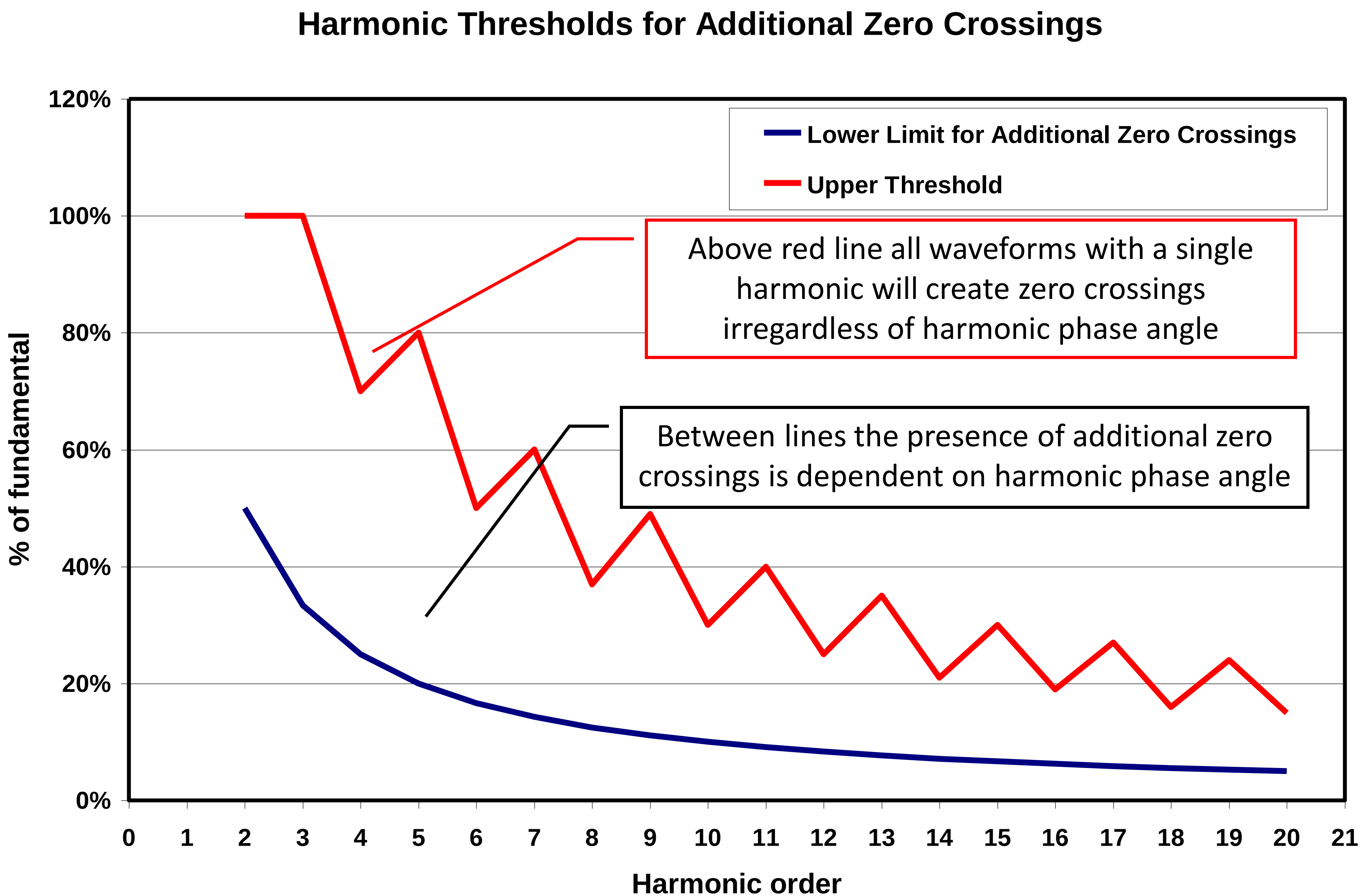
Current Peak with Harmonics >2 Times Normal –large 8th Harmonic could only be produced by DC-caused half-cycle saturation
Harmonic Impedance of Load is very Important Root-Cause of this Impact Case

	HQ-I	HQ-V
TVD	131.86%	7.34%
THD	131.86%	7.34%

Case Studies - Fuse Operation on 60kVAR power factor correction capacitor bank

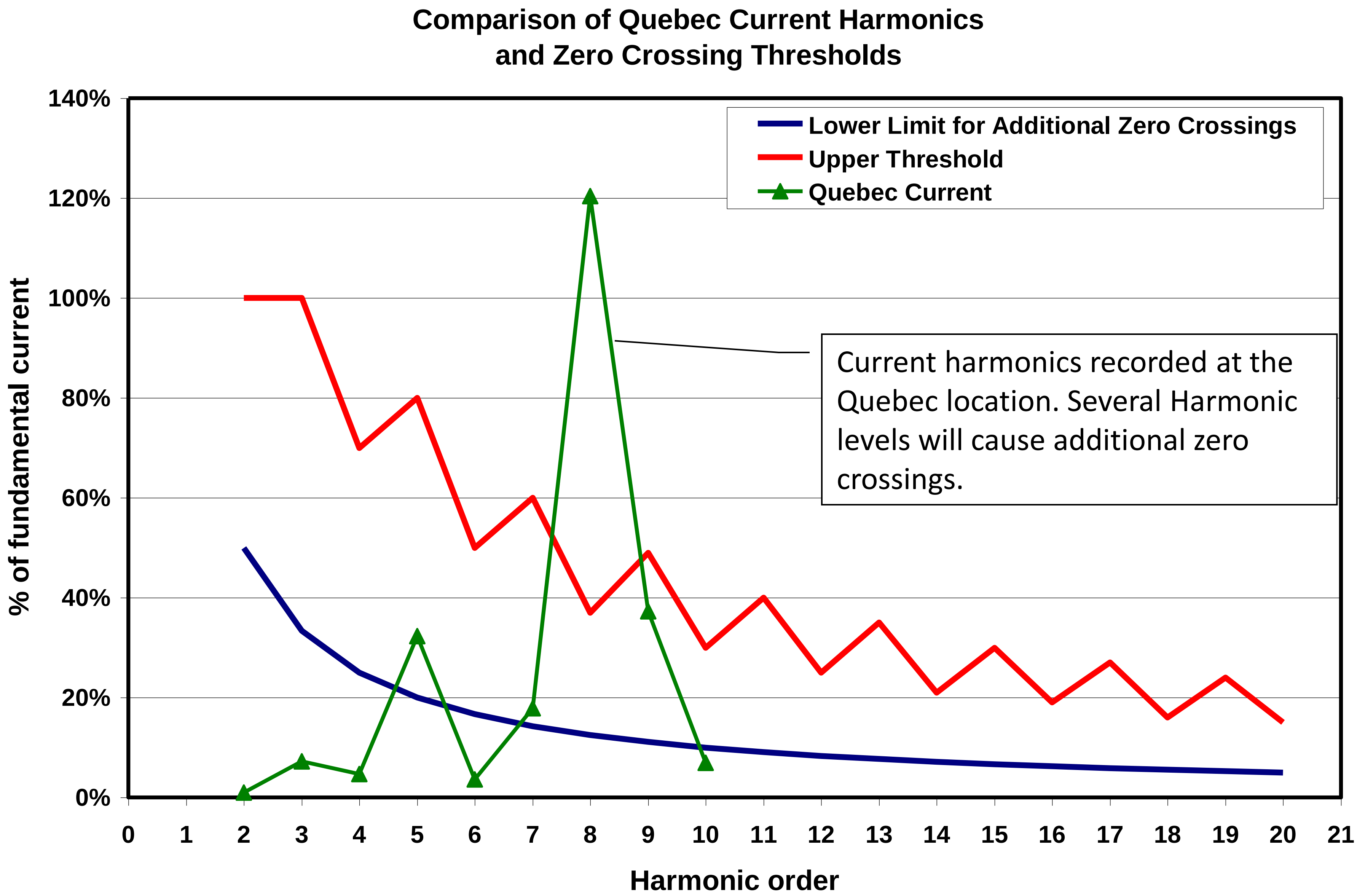


Individual Harmonics & Additional Zero Crossings

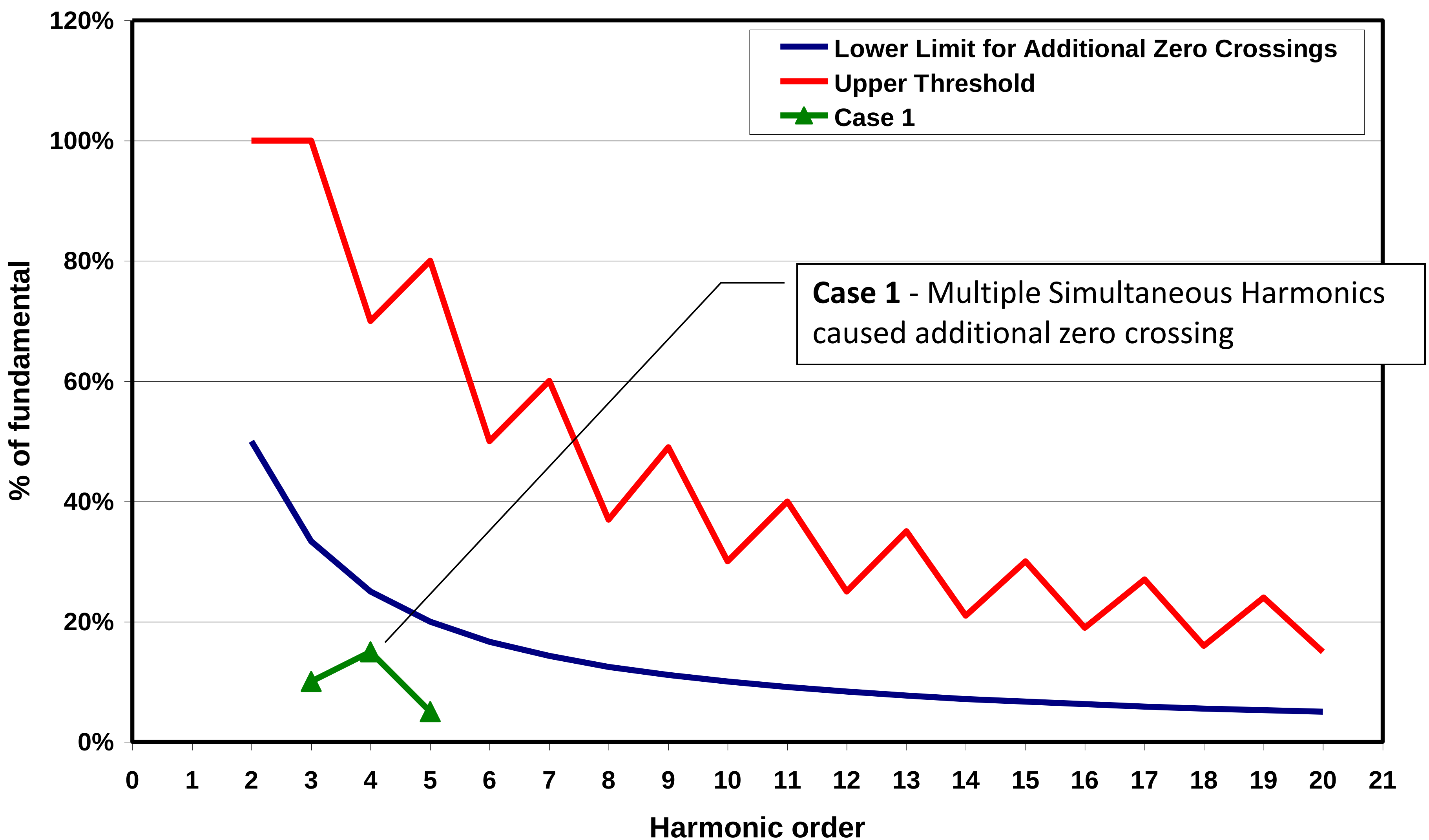


Storm Analysis Consultants

Individual Harmonics & Additional Zero Crossings



Multiple Harmonics & Additional Zero Crossings

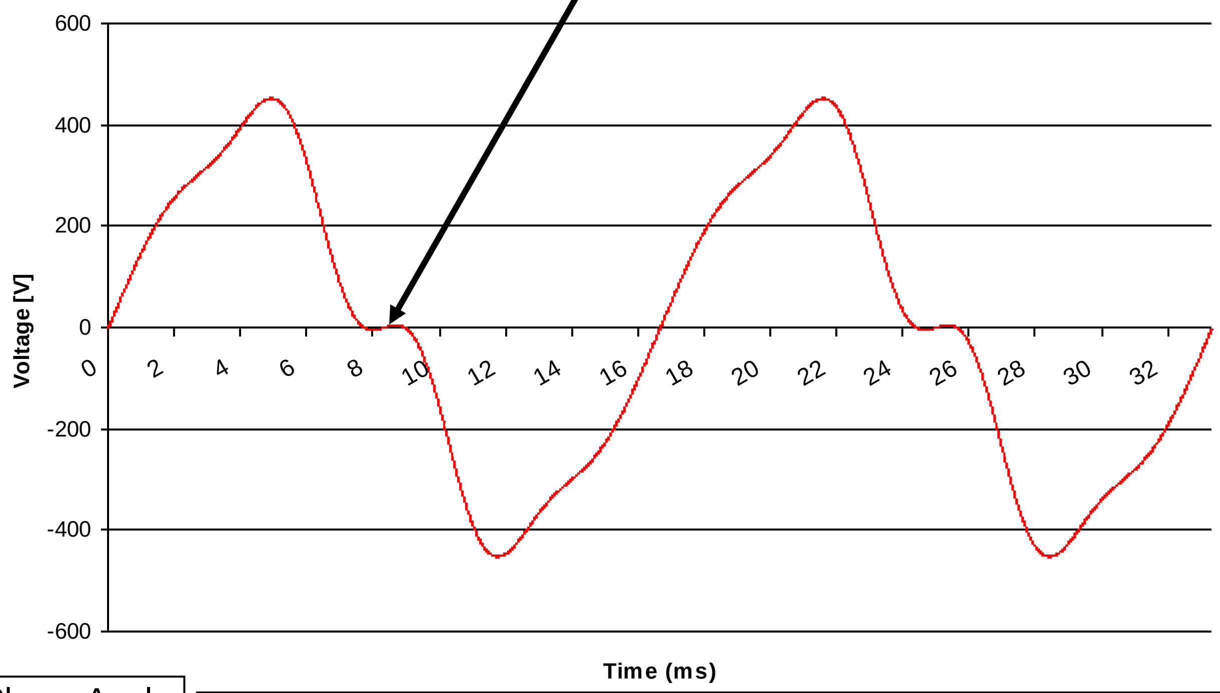


Storm Analysis Consultants

Multiple Harmonics & Additional Zero Crossings

Test - sum of multiple harmonics at optimal phase angles when $V_1 < \Sigma V_h * h$.
V1 equals 277V-rms and the sum of harmonics times their order equal 319V-rms

Additional zero crossings near 180 degrees



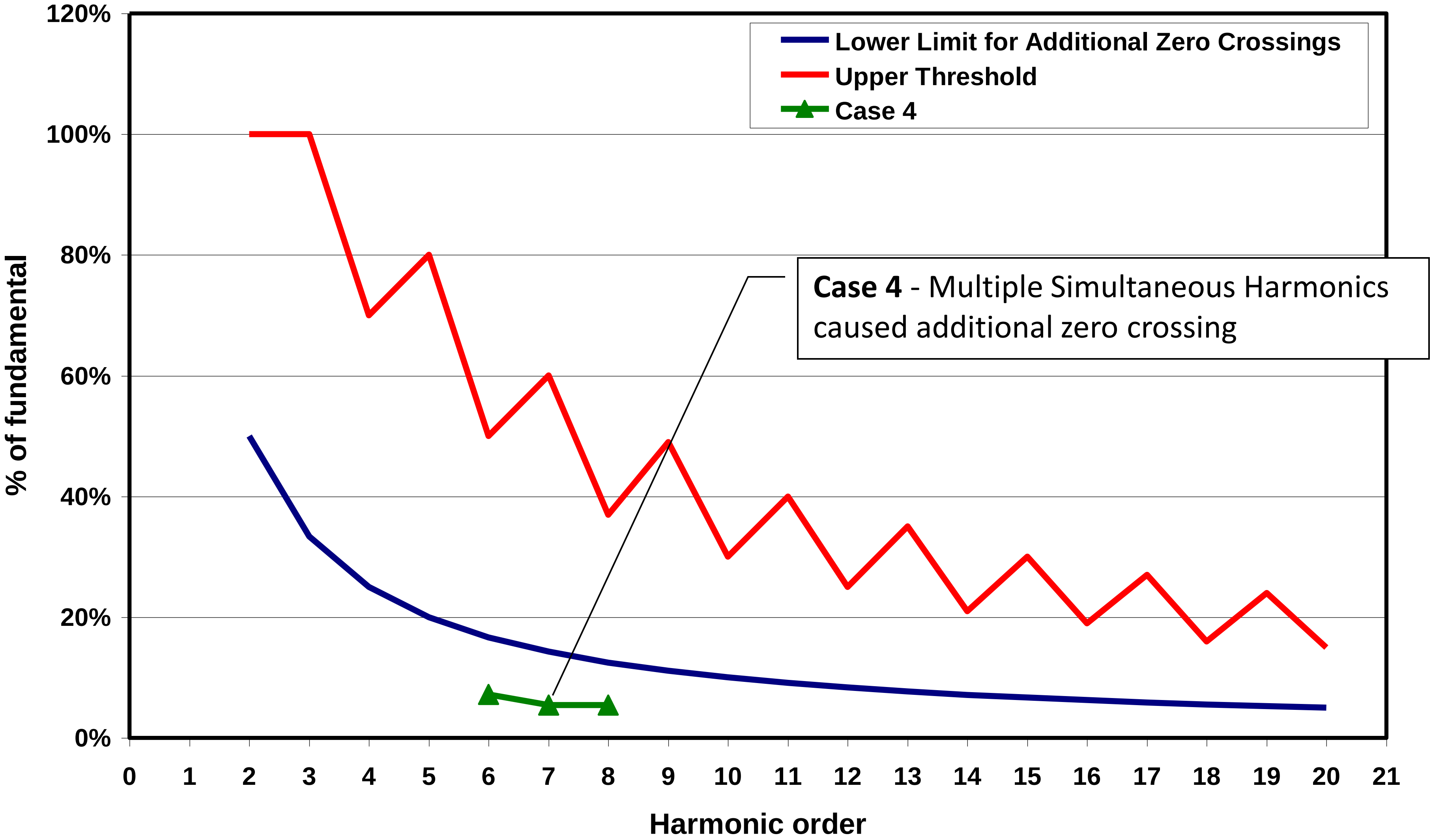
Harmonic	Magnitude	Phase Angle
1	277	0
3	27.7	180
4	41.55	0
5	13.85	180

Case 1: 3rd, 4th & 5th Harmonics Present

$V_1 < \Sigma V_h * h$ and V_1 = 277V-rms

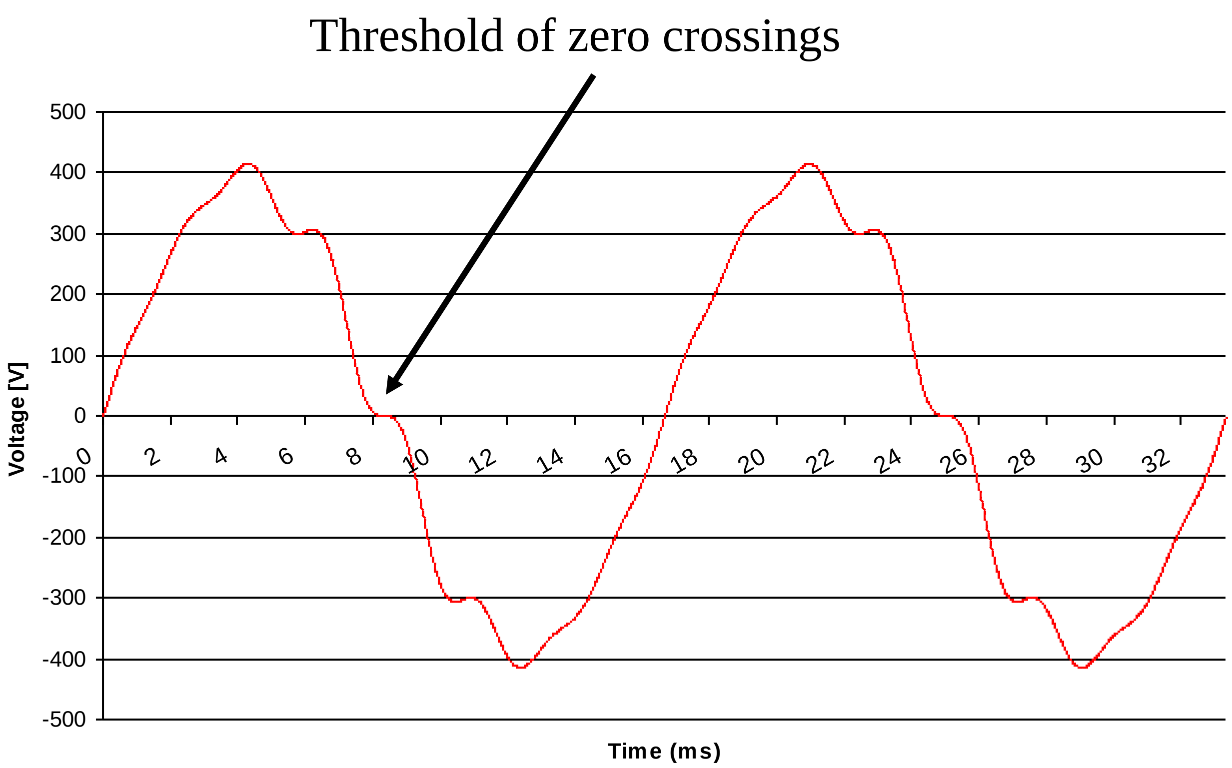
$\Sigma V_h * h = (27.7 * 3)+(41.55 * 4)+(13.85 * 5) =$ **319V-rms**

Multiple Harmonics & Additional Zero Crossings



Multiple Harmonics & Additional Zero Crossings

Threshold of causing additional zero crossing.



Harmonic	Magnitude	Phase Angle
1	277	0
6	10	180
7	15	0
8	14	180

Decreased 6th by 10 V-rms and 8th order by 1 V-rms

$V_1 > \Sigma V_h * h$ and $V_1 = 277V$

$\Sigma V_h * h = (10 * 6) + (15 * 7) + (14 * 8) =$ **277 V-rms**

Storm Analysis Consultants